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ENERGY RESEARCH CORP DANBURY CONN
1.5KW METHANOL FUEL CELL POWERPLANT. (U)
APR 78 S G ABENS, M LAMBRECH, P MARCHETTI

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6 1.5kW METHANOL FUEL CELL POWERPLANT.

9 FINAL TECHNICAL REPORT.

10 By
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SUMMARY

A 1.5kW indirect methanol fuel cell powerplant was designed, constructed, tested, and delivered to MERADCOM.

The powerplant operates on a 1:1.3 molar mixture of methanol and water, which is converted in a steam reformer, operating at 400°F, to hydrogen-rich product gas for use in the fuel cell. The fuel cell converts 75% to 80% of the hydrogen to electrical energy. The balance of the feed gas (bleed stream) is combusted in a burner to supply heat required for the endothermic reforming process. Additional reaction energy is supplied by combusting some liquid methanol-water feed in the burner. The fuel cell stack which operates at a temperature of 300 to 330°F is an air-cooled, bipolar plate type using a phosphoric acid electrolyte. A voltage regulator is used to regulate the stack output voltage to an adjustable 26-34V output. An automatic control unit provides event sequencing during start-up and shutdown and system control for unattended operation of the powerplant.

The powerplant was tested under room ambient conditions at power levels from idle to the maximum requirement of 1.65kW. Fuel consumption varied from 1.1 lbs/hr at idle to 3.3 lbs/hr at 1.65kW. At 1.65kW, the efficiency of the fuel cell stack based on cell voltage was 38.7%, and the overall thermal efficiency of the powerplant was 16.6%. Powerplant operation was automatic during performance testing, except for manual adjustment of the rate of fuel supply.

1.0 INTRODUCTION

The purpose of this project was the design, demonstration, and delivery to USA MERADCOM of a 1.5kW methanol fuel cell powerplant.

The long range objective of this program is to develop a silent, long-life portable electric power generator. The basic features of a phosphoric acid fuel cell powerplant make it a very attractive choice for this application. Methanol is used as the fuel since it can be easily stored and transported and can be readily reformed to a hydrogen-rich gaseous fuel for operation of the fuel cell stack.

Phosphoric acid fuel cell manufacturing processes designed to be compatible with mass production techniques had been developed earlier at ERC on programs supported by USA MERADCOM.⁽¹⁾ This technology was employed for construction of the 80-cell stacks used as the prime mover of the powerplant. The fuel conditioning and automatic control unit as well as the system concepts were developed as part of this project; the required voltage regulator was supplied by MERADCOM.

The project was conducted in three phases. The first phase was dedicated to subsystem development and testing. During this phase, a methanol steam reformer, an 80-cell bipolar plate fuel cell stack, and the automatic control logic and basic circuitry were developed.

During the second phase, fabrication and testing of the subsystem components was conducted. A breadboard powerplant was assembled and operated in accordance with the powerplant load requirements. Fuel cell stack performance levels on steam reformed methanol fuel were established and the basic subsystem integration concepts were verified. The control logic used in the design of the automatic control unit (ACU) was also verified.

Powerplant assembly and testing were accomplished during the final phase of the program. The testing included establishment of fuel consumption figures from idle to the required 10% overload operating conditions. At the completion of the project, an operational 1.5kW powerplant was delivered to USA MERADCOM, Ft. Belvoir, VA.

Also as part of the contractual effort, an analysis was performed to identify methods suitable for recovery of the water produced by the powerplant for recirculation to the reformer.

2.0 POWERPLANT DEVELOPMENT

2.1 Powerplant Specifications

Specifications for the 1.5kW methanol-air fuel cell powerplant which was under development on this program are summarized in Table 1.

TABLE I

POWERPLANT SPECIFICATIONS

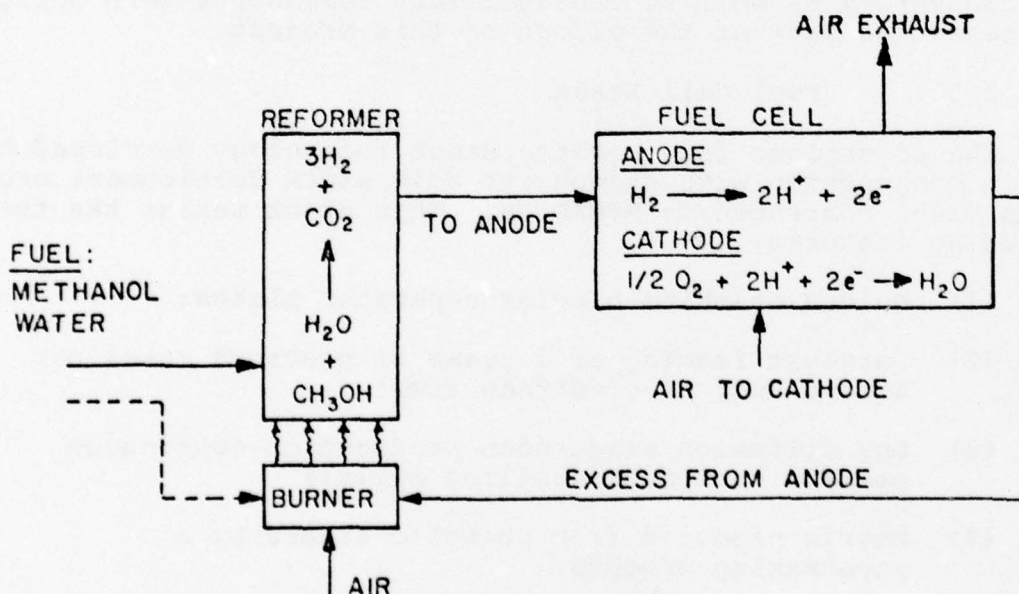
1. Power Output - 1.5kW net DC at an adjustable voltage of 24 to 34 volts. The unit shall be capable of operation at 110% rated load for one hour in every four.
2. Fuel - Methyl Alcohol, Federal Specification O-M-232e, Grade AA.
3. Water - Deionized
4. Weight 175 lbs maximum.
5. Volume - 8 ft³ maximum; 5 ft³ design goal, with no linear outside dimension exceeding 2.5 ft
6. Fuel Consumption - 1.2 lbs methyl alcohol per net KWH maximum.
7. Load Response - Automatic-full load to no load and no load to full load.

8. Start-up - Automatic - 15 minutes maximum at ambient temperatures of -25°F to 125°F.
9. Operation - Automatic - completely unattended.
10. Shut-Down - Manual activation of a single switch after removal of external load.
11. Noise Level - Inaudible at 100 meters (328 ft) when operating at any load level.
12. Reliability and Availability - 95% Reliability with a confidence level of 90% for a 24 hour mission, with an inherent availability rate of 98%. Test time determined on 2 defects basis.
13. Endurance - No major maintenance for 3000 hours of operation.

2.2 System Design

The methanol fuel cell powerplant is based on the phosphoric acid fuel cell operating at 300 - 350°F. The fuel is hydrogen-rich reformer product gas derived by steam reforming of methanol at 400 - 450°F. Process air to the fuel cell stack is supplied by a blower; the same air stream is used to maintain stack operating temperature at 300 - 330°F. The reactions involved are summarized in the flow diagram shown in Figure 1.

FIGURE 1



INDIRECT METHANOL FUEL CELL

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Excess water is used in the actual operation of the reformer in order to obtain complete conversion of methanol; also, a small amount (less than 1%) of by-product CO is produced. To achieve efficient fuel cell operation, a 20-30% excess of fuel is supplied; this fuel passes thru the stack and is burned in the reformer burner to supply heat for the endothermic reforming reaction.

The 1.5kW methanol powerplant design comprises four basic subsystems which have the following functions:

<u>Subsystem</u>	<u>Function</u>
1. Methanol Reformer	Converts methanol and water to hydrogen and carbon dioxide
2. Fuel Cell Stack	Produces unregulated DC power from hydrogen and air
3. Voltage Regulator	Regulates powerplant output voltage to desired value (26-34 VDC)
4. Automatic Control Unit	Provides automatic control for startup, shutdown, and load changes.

Except for the voltage regulator, which was supplied by MERADCOM, the subsystems as well as the ancillary components were designed and tested as part of the effort on this project.

2.3 Fuel Cell Stack

The powerplant incorporates stack technology developed by ERC in conjunction with phosphoric acid stack development programs under contracts to MERADCOM. This stack design has the following features:

- (1) Molded graphite bipolar separator plates;
- (2) Catalyst loading of 2 grams of precious metal per square foot of electrode area;
- (3) Gas diffusion electrodes produced on continuous process equipment (rolling mills);
- (4) Matrix produced from phenolic fibers by a papermaking process;
- (5) Electrolyte addition to the stack by wicking from an external electrolyte supply.

The above stack features were developed with the purpose of making components manufacturing compatible with mass production processes. In this section, components and cell characteristics of the phosphoric acid fuel cell stacks employed for construction of the 1.5kW powerplants are briefly described.

2.3.1 Electrodes

The gas diffusion electrodes employed in the stacks are produced by laminating a thin catalyst layer to a graphite paper support layer. Catalyst materials are platinum black in the cathode and a mixture of platinum and rhodium in the anode.

The catalyst layer is produced in several steps. The catalyst, polytetrafluoroethylene (PTFE) and a pore-forming agent (ammonium bicarbonate) are mixed intimately and calendered to a thin layer. This layer is heated to remove the NH_4HCO_3 and pressed onto the support layer, which has been impregnated with PTFE to render it wetproof. The electrodes are heated prior to assembly in the stack to complete the wetproofing process.

The above electrode process has been described in detail previously ⁽²⁾. It has been recapitulated here in the process flow diagram shown in Figure 2.

The final thickness of the electrodes varies over the range of 0.016 to 0.019 in.; the catalyst layer itself measures about 0.001 in. thick. The final cut dimensions of the anode and the cathode are shown in Figure 3.

2.3.2 Bipolar Plates

The bipolar separator plates used in building the stacks were compression molded from a mixture of two graphites (Asbury Graphite Mills A-99 and Micro 850 in a weight ratio of 11 to 4) and a phenolic molding resin (Colloid Chemical Labs 8440); resin content in the mix was 33% by weight.

The plates were produced by a compression molding technique described previously ⁽²⁾. The molding process is also summarized in the flow diagram shown in Figure 4.

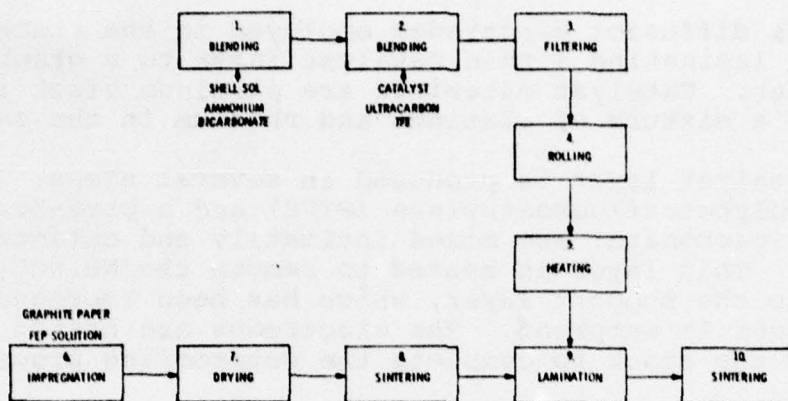
Figure 5 shows the design of the plates. Plate weight was maintained between 195 and 215 grams, which produced thickness in the range of 0.165 to 0.175 in. The plates are complete as molded, except for two 3/16 in. diameter electrolyte fill holes which are drilled.

2.3.3 Matrix

The Kynol fiber matrix was produced by the papermaking process described previously ⁽²⁾. A process flow diagram is reproduced here for reference as Figure 6. Thickness of the

FIGURE 2

Electrode Manufacturing Process



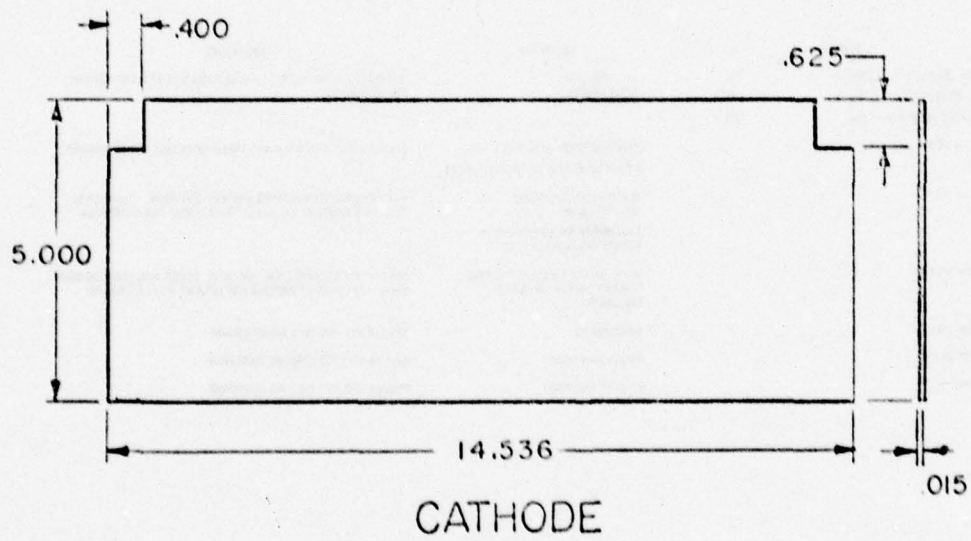
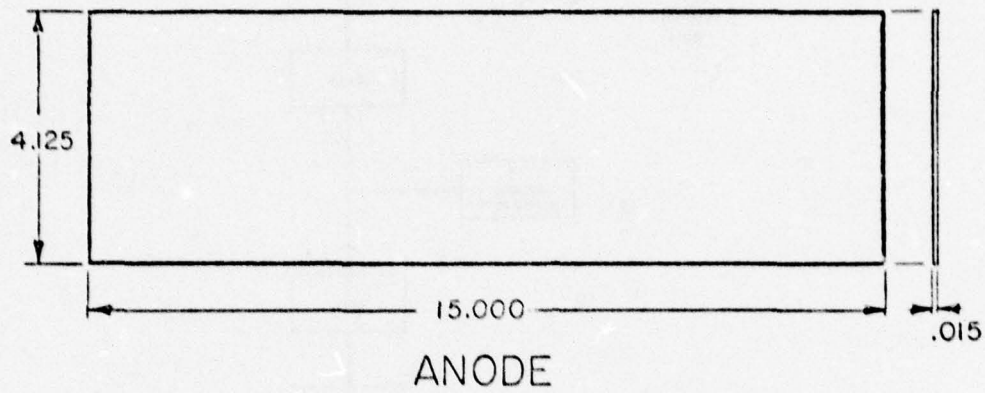
STEP	MATERIAL	EQUIPMENT	PROCEDURE
1	SHELL SOL 40001 AMMONIUM BICARBONATE 130g (1)	WARING BLENDOR MODEL CB-6	TRANSFER ALL MATERIAL TO BLENDOR AND MIX AT "LOW" SETTING FOR 2 MINUTES
2	FROM STEP 1 ANODE ONLY ADAMS' PT OXIDE 4.7g (2) ADAMS' RN OXIDE 4.2g (2) ADAMS' NI OXIDE 1.0g (2) TUNGSTEN OXIDE 1.4g (3) CATHODE ONLY PLATINUM BLACK 7.0g (4) ULTRACARBON 0.7g (5) TFC 2g 100	WARING BLENDOR MODEL CB-6	TRANSFER ALL MATERIAL TO BLENDOR AND MIX AT "LOW" SETTING FOR 2 MINUTES
3	FROM STEP 2	BUCHNER FUNNEL 8" I. D.	TRANSFER MATERIAL TO FUNNEL AND FILTER UNTIL FREE OF LIQUID.
4	FROM STEP 3	ROLLING MILL C. A. M. I. L. 574312755	ROLL TO SIZE, 11 x 46 in. CUT 8 PIECES, 5 x 15 in.
5	FROM STEP 4	OVEN, NEW ENGLAND OVEN AND FURNACE COMPANY MODEL C450	HEAT FOR 30 MINUTES IN AIR AT 75°C BETWEEN PAPER
6	GRAPHITE PAPER 5 x 15 in. FEP TYPE 120, 0N SOLUTION IN D. I. WATER 100	BATH 20 x 6 x 3 in.	IMMERSE IN BATH FOR 2 MINUTES
7	FROM STEP 6	RACK	SUPPORT WET SHEETS VERTICALLY AND DRY IN AIR FOR 2 HOURS
8	FROM STEP 7	OVEN, BLUE M ELECTRIC COM- PANY, 26.5 FT ³ CONVECTION 0-1400°F	HEAT FOR 15 MINUTES AT 315°F
9	FROM STEP 8	PRESS, J. H. WOOD CO. 40 TON	PRESS 5 x 15 in. SHEETS
10	FROM STEP 9	OVEN, BLUE M ELECTRIC COM- PANY, 26.5 FT ³ FORCED CON- VECTION 0-750°C SINTERING BOX (7) NITROGEN DRY	PLACE IN SINTERING BOX, START N ₂ FLOW AT 25 ml/min. PLACE BOX IN PREHEATED OVEN AND HOLD AT TEMPERATURE FOR 15 MINUTES. NOTE B

NOTES:

- ANALYTICAL REAGENT, FISHER SCIENTIFIC CO.
- ADAMS' PROCESS, ORGANIC SYNTHESIS, R. ADAMS ED. 1930
- ANALYTICAL REAGENT, MALINKRODT, INC.
- FUEL CELL GRADE, ENGELHARD INDUSTRIES
- UCP 1-M, ULTRA CARBON CORPORATION
- DUPONT
- DWG. NO. 132714071
- NBC FOR ANODE, MDC FOR CATHODE

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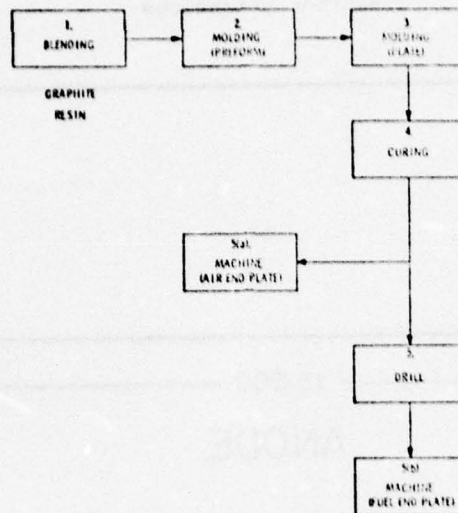
FIGURE 3
Electrode Dimensions



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FIGURE 4

Bipolar Plate Manufacturing Process



STEP	MATERIAL	EQUIPMENT	PROCEDURE
1	A-99 GRAPHITE 110g B-99 GRAPHITE 40g ARYLENE APP RESIN 75g	(1) SIGMA MIXER STYLE 200014 (2) (3)	TRANSFER ALL MATERIALS TO MIXER AND MIX AT "LOW" SETTING FOR 10 MINUTES.
2	FROM STEP 1	PREFORM MOLD, DWG. 132214670 4 POST UP ACTING HYDRAULIC PRESS	LEVEL MATERIAL IN MOLD AND PRESS AT 15 TONS FOR 10 SECONDS.
3	FROM STEP 2	PLATE MOLD (PLATE DWG. NO. 132214654) SOUTHWARK 400 TON 4 POST UP ACTING HYDRAULIC PRESS	TRANSFER PREFORM TO MOLD PREHEATED TO 300°F. HOLD FOR 10 SEC. THEN PRESS AT 150 TONS FOR 6 MINUTES AND DISCHARGE.
4	FROM STEP 3	OVEN, BLUE M ELECTRIC COMPANY, FORCED CONVECTION 76.5 FT ³ 100-1100°F	PLACE PLATE BETWEEN TWO THICK AL. PLATES AND PLACE IN COLD OVEN. HEAT OVEN AT 100°F/HR AND HOLD AT 375°F FOR 6 HOURS.
5	FROM STEP 4	DRILL PRESS	DRILL HOLES PER DWG. NO. 132214654
6	FROM STEP 4	MILLING MACHINE	MILL GROOVE PER DWG. NO. 132214663
7	FROM STEP 5	MILLING MACHINE	MILL GROOVE PER DWG. NO. 132214662

NOTES:

1. ASBURY GRAPHITE MILLS, INC.

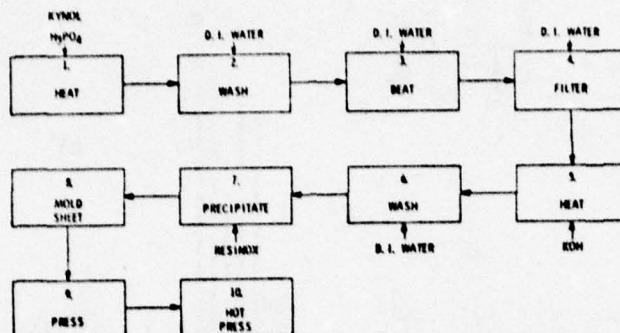
2. ASHLAND CHEMICAL COMPANY

ALTERNATE MATERIAL: COLLOID 8440 RESIN, COLLOID CHEMICAL LABORATORIES, INC.

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FIGURE 6

Matrix Manufacturing Process



STEP	MATERIAL	EQUIPMENT	PROCEDURE
1	KYNOL 42% H ₃ PO ₄ 85%	(1) "LIGHTNING" MIXER MODEL NO-1-PVM (2) THERMODYNE HOT PLATE TYPE 2200	MIX KYNOL WITH COLD H ₃ PO ₄ . STIR AT ("LOW") AND BRING TO 275°F IN 1 HOUR. CONTINUE TO STIR FOR 3 HOURS. COOL.
2	FROM STEP 1 DEIONIZED WATER	18" BRASS SHEET MOLD NOBEL AND WOOD COMPANY FILTER PAPER	WASH IN SHEET MOLD WITH WATER TO pH = 7
3	FROM STEP 2 DEIONIZED WATER	FIBER BEATER - FULTON MFG. DIV.	CIRCULATE IN BEATER FOR 1 HOUR WITH WATER AS NEEDED
4	FROM STEP 3 DEIONIZED WATER	NOBEL & WOOD MACHINE CO. 18" BRASS SHEET MOLD FILTER PAPER	FILTER EXCESS WATER
5	FROM STEP 4 KOH 30% 1 L	(3) "LIGHTNING" MIXER MODEL NO-1-PVM THERMODYNE HOT PLATE TYPE 2200	MIX KYNOL WITH COLD KOH. STIR ("LOW" SETTING) AND BRING TO 200°F IN 1/2 HOUR. CONTINUE TO HEAT FOR 1 HOUR. COOL.
6	FROM STEP 5 DEIONIZED WATER	18" BRASS SHEET MOLD NOBEL & WOOD MACHINE CO., FILTER PAPER	WASH IN SHEET MOLD WITH WATER TO pH = 7
7	FROM STEP 6 RESINOX 14 ml	(4) WABASH BLENDOR MODEL 91-263	DILUTE KYNOL WITH WATER TO 1000 ml. ADD 14 ml RESINOX. BLEND FOR 15 MIN. ("MEDIUM"), GRADUALLY BRING pH TO 4.5 WITH H ₂ SO ₄ . STIR 3 MINUTES.
8	FROM STEP 7	18" BRASS SHEET MOLD NOBEL AND WOOD MACHINE COMPANY	FILL MOLD TO 3/4 LEVEL WITH WATER. ADD MATERIAL. AGITATE BY HAND. FORM SHEET.
9	FROM STEP 8	WATSON-STILLMAN 4 POST UP ACTING HYDRAULIC PRESS	PRESS WET SHEET BETWEEN FILTER PAPERS AT 75 TONS
10	FROM STEP 9	WABASH - 4 POST UP ACTING HYDRAULIC PRESS WITH TEMPERATURE CONTROL	AIR DRY OVERNIGHT. THEN PRESS TO 0.025" (ISHIMIZI) AT 300°F FOR 15 MINUTES AND CUT TO SIZE 5 x 15 IN.

NOTES:

1. KYNOL - BLOWN PHENOLIC FIBER, AMERICAN KYNOL CORP.
2. H₃PO₄ - BAKER ANALYZED REAGENT
3. KOH - BRAND MU LABS
4. RESINOX - MONSANTO RI 0216, 35% SOLIDS
5. H₂SO₄ - BAKER ANALYZED REAGENT
6. FILTER PAPER - MEDIUM FINE POROSITY, FILTERS 90% OF 8 MM PARTICLES AT MEDIUM FLOW RATE

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matrix was maintained at 0.017 to 0.019 in., and its porosity was 55 to 60%. The cut dimensions of the matrix are shown in Figure 7.

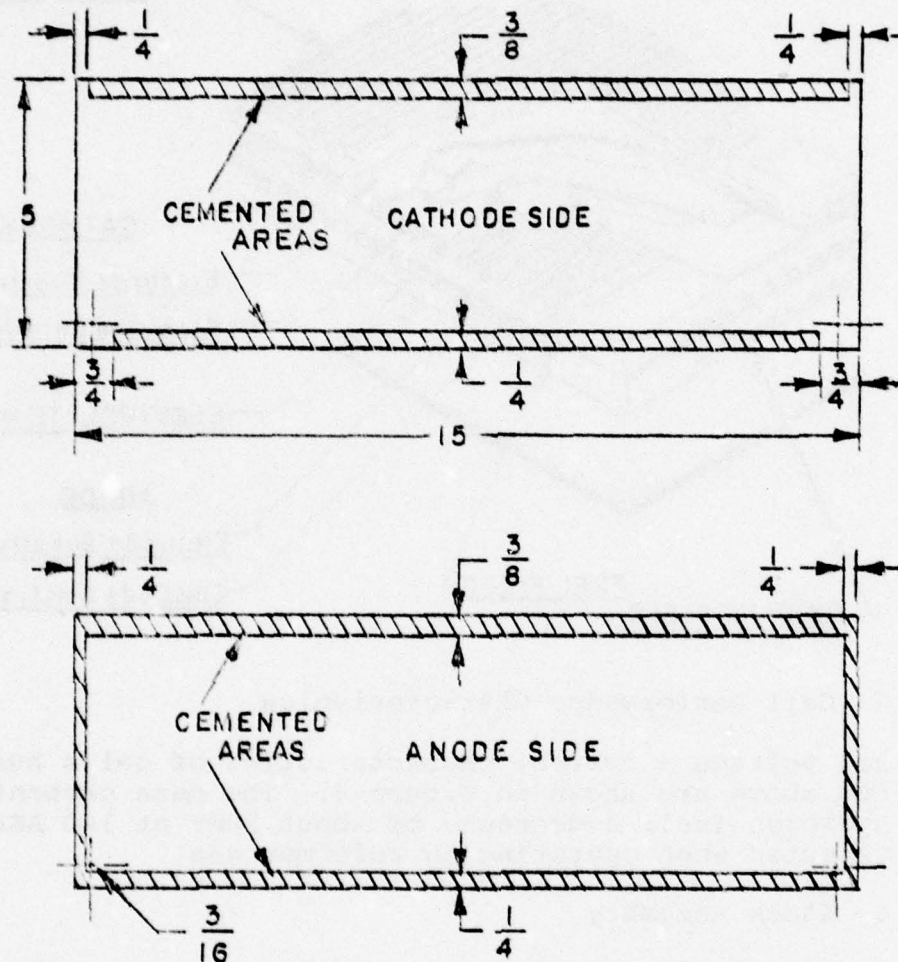


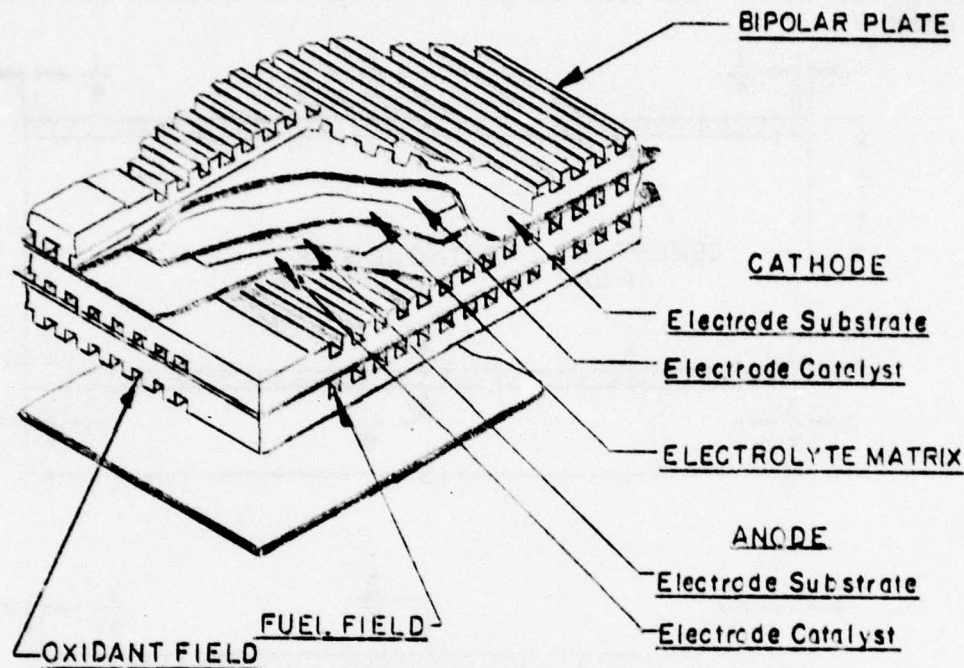
FIGURE 7 MATRIX DIMENSIONS

2.3.4 Cell Assembly

Bipolar plates, electrodes, and matrices were stacked alternately in the conventional fashion to produce multicell stacks. A fluorolastomer cement (C0328 VITON RTV CEMENT, The Connecticut Hard Rubber Co.) was applied at the edges of the matrix and the electrodes. Tantalum metal shims were placed over the edges of the fuel side of the plate, and TFE film inserts were used over the seal area on the air side to produce a gas-tight assembly. Cross-sections of the cell in the directions of air and of fuel flow are shown in Figure 8.

Filling of the matrices with electrolyte is accomplished by supplying electrolyte to the fill channels from an external reservoir while maintaining the stack at 270-300°F.

FIGURE 8 CELL CROSS-SECTIONAL VIEW



2.3.5 Cell Performance Characteristics

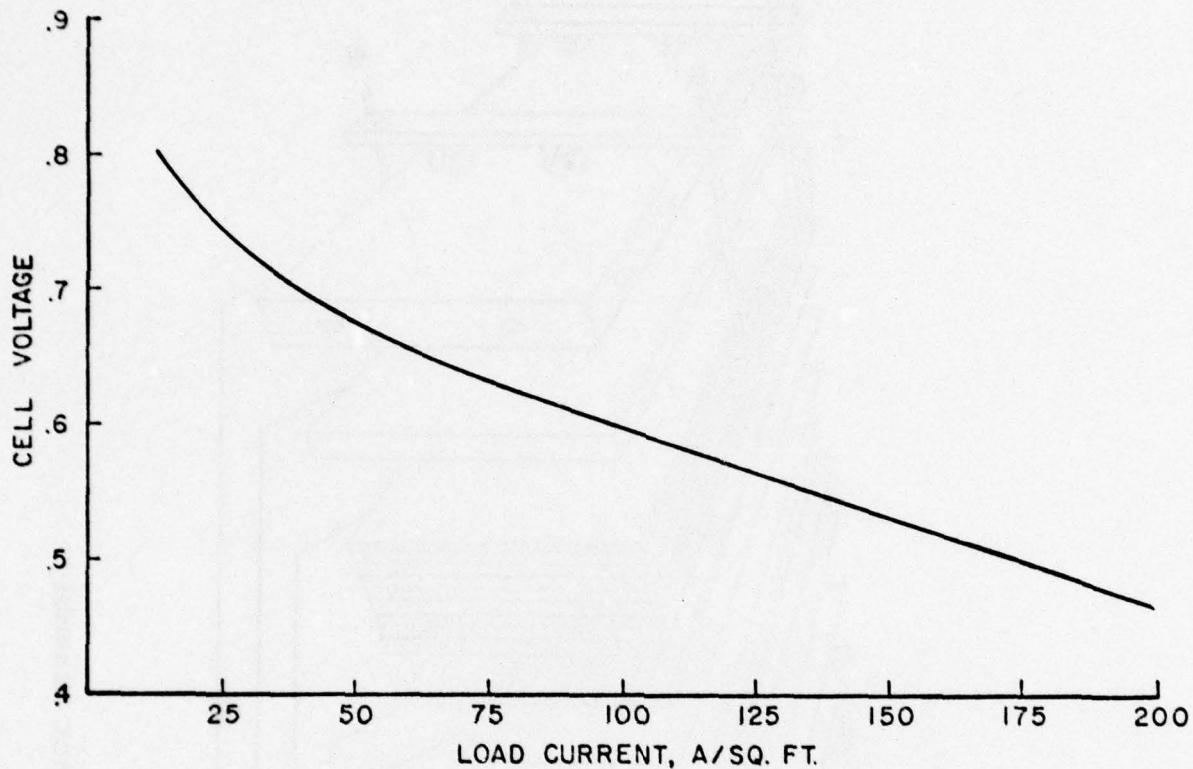
Typical voltage - current characteristics of cells built as described above are shown in Figure 9. The data presented are for pure hydrogen fuel; a decrease of about 20mV at 100 ASF is normally expected when operating on reformer gas.

2.3.6 Stack Assembly

An 80-cell stack utilizing the cell features described was used for the 1.5kW powerplant. This cell number was chosen to assure sufficient stack output voltage under all operating conditions and to provide for voltage reduction resulting from operation on reformer gas rather than on neat hydrogen as well as for normal cell performance decay (a maximum voltage decay rate of 10 μ V/hr can be anticipated for the electrode design employed).

The 80-cell stack was supported between aluminum endplates and epoxy-fiberglass insulating plates. Electrical heating mats were placed between the insulators and endplates to provide for stack heating during electrolyte fill and stack idle periods. The complete assembly was compressed with compression bars and tie rods to 4 tons. The stack assembly complete with compression bars and tie rods is picture in Figure 10.

FIGURE 9 CELL CHARACTERISTICS



2.3.6.1 Gas Manifolds

Fuel and air manifold designs for the 80-cell stack are shown in Figure 11. The manifolds were fabricated from 0.020 in. thick aluminum with U-channel reinforcements over the seal areas. The manifold-to-stack seal was obtained by the use of Viton rubber gasketing.

2.3.6.2 Process Air Supply

The 80-cell stack was designed to operate with process air outlet temperature of 280-320°F and an air inlet temperature range of 130-270°F depending on powerplant load conditions. Air to the stack is supplied by a 28V, 400 Hz blower (Rotron Model # 1792JF Propi-Max 3B) located in the process air duct as shown in Figure 12. Stack temperature control is obtained by a damper in the recirculating duct, which changes the ratio of fresh to recirculated air flowing to the stack. The air flow rate thru the stack was about 90 CFM with the stack operating at rated power (1.9kW). The fully assembled 80-cell stack is pictured in Figure 13.

2.3.7 Stack Performance Characteristics

A total of five 80-cell, 2kW stacks were constructed and evaluated in the course of this program. Except for minor

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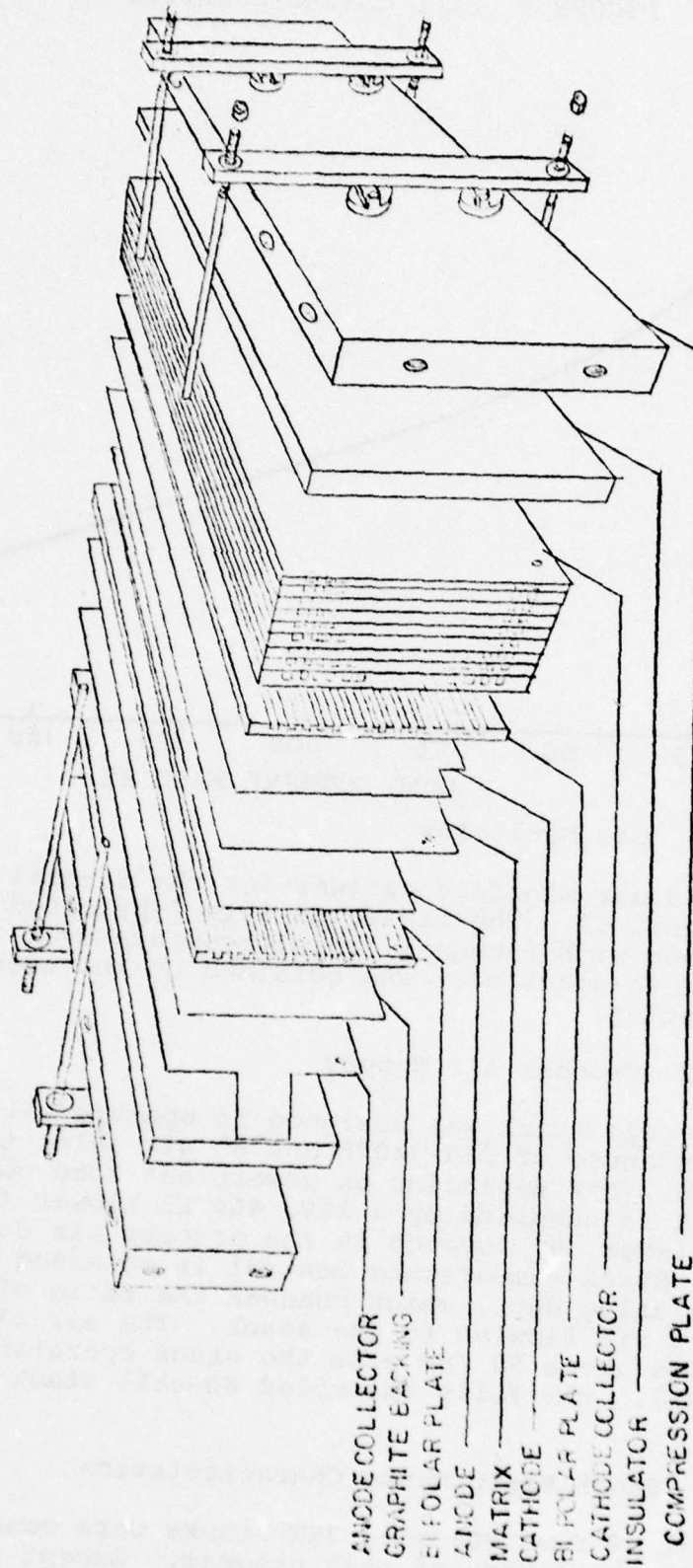
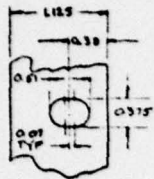


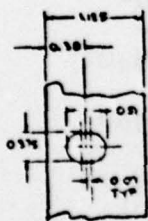
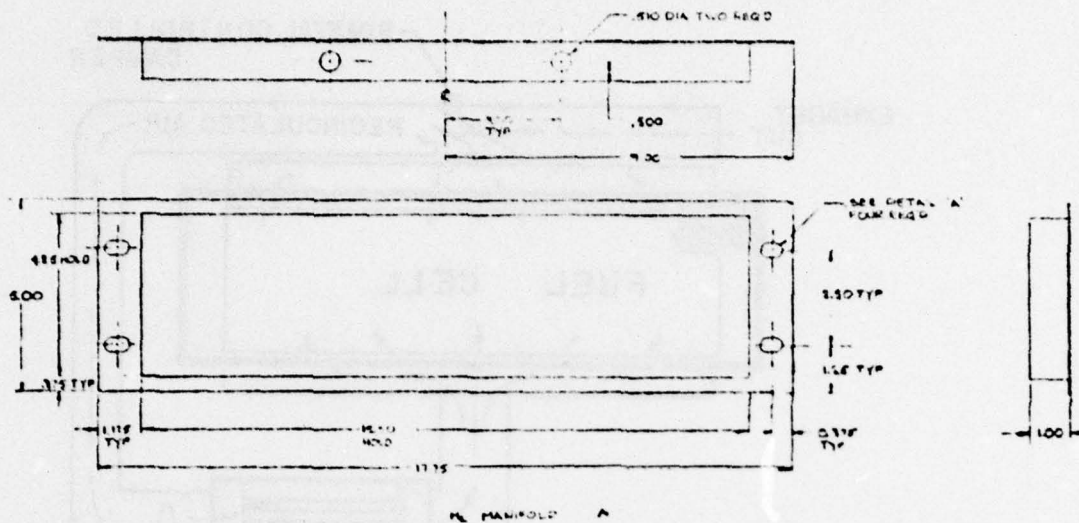
FIGURE 10 Stack Assembly

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SCALE - FULL



DETAIL - A
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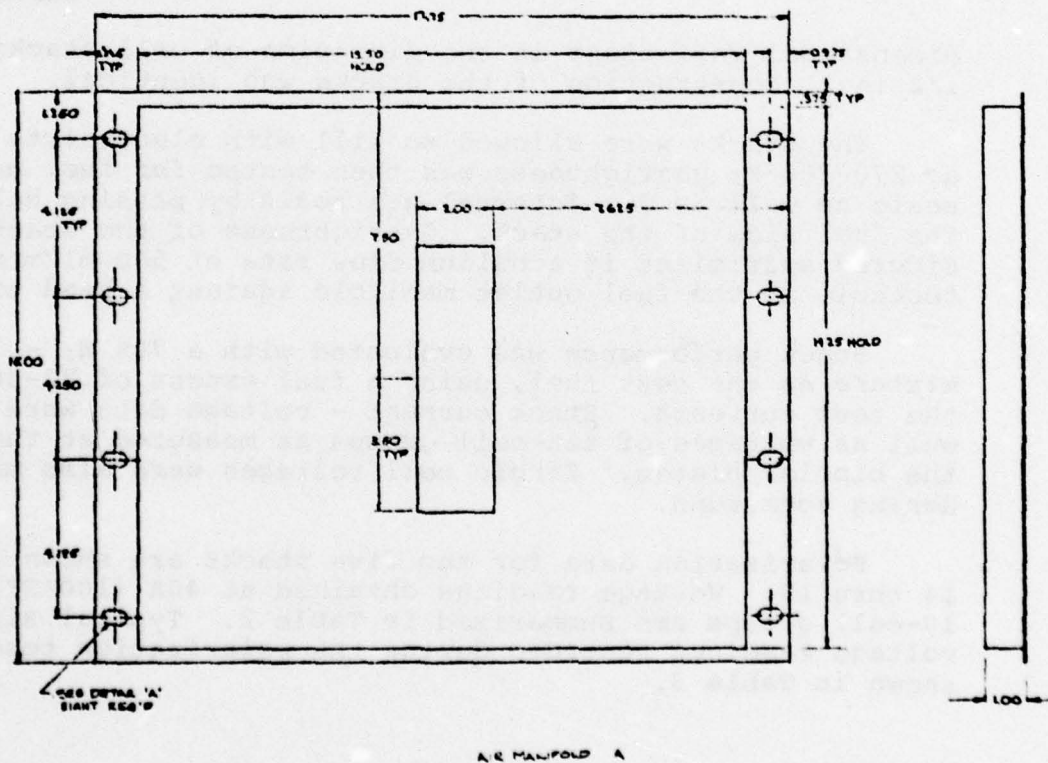
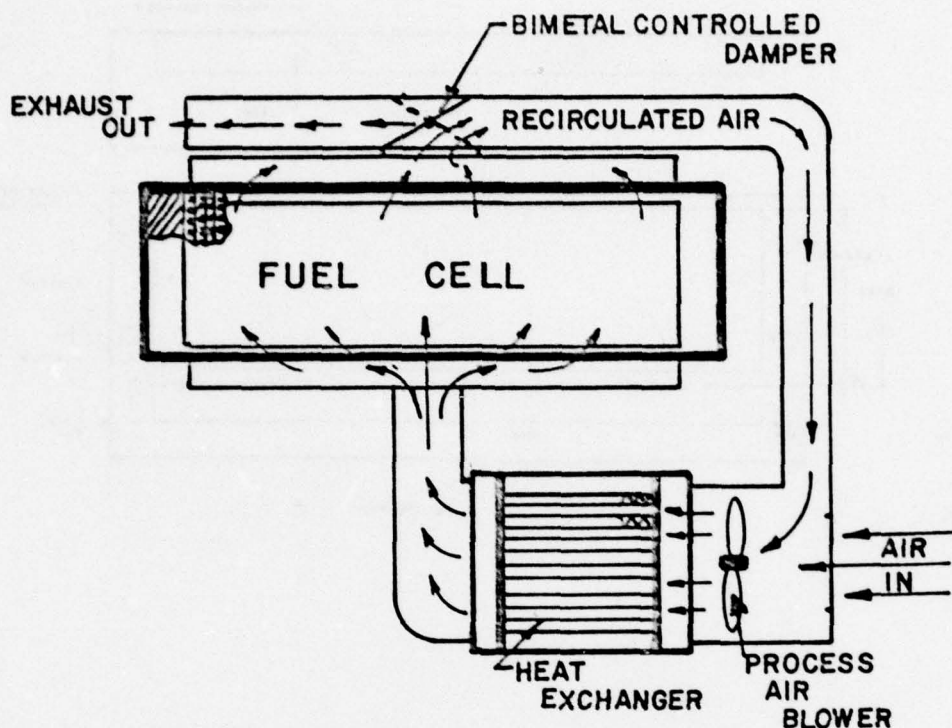


FIGURE 11 Stack Gas Manifolds

FIGURE 12 Stack Air Blower



dimensional variations in the direction of cell stacking (under 1/2 in.), construction of the stacks was identical.

The stacks were allowed to fill with electrolyte for 5 days at 270-300°F; gastightness was then tested for fuel manifold seals as well as for internal gas seals by passing helium thru the fuel side of the stack. Gastightness of the stack was considered sufficient if a helium flow rate of 500 ml/min was detectable at the fuel outlet manifold against a head of 1" of H₂O.

Stack performance was evaluated with a 70% H₂ - 30% CO₂ gas mixture as the test fuel, using a fuel excess of 20-30% at any of the test currents. Stack current - voltage data were recorded as well as voltages of ten-cell groups as measured at the edges of the bipolar plates. Single cell voltages were also monitored during some runs.

Polarization data for the five stacks are shown in Figures 14 thru 18. Voltage readings obtained at 40A (100ASF) for the 10-cell groups are summarized in Table 2. Typical single cell voltage readings recorded during the polarization tests are shown in Table 3.

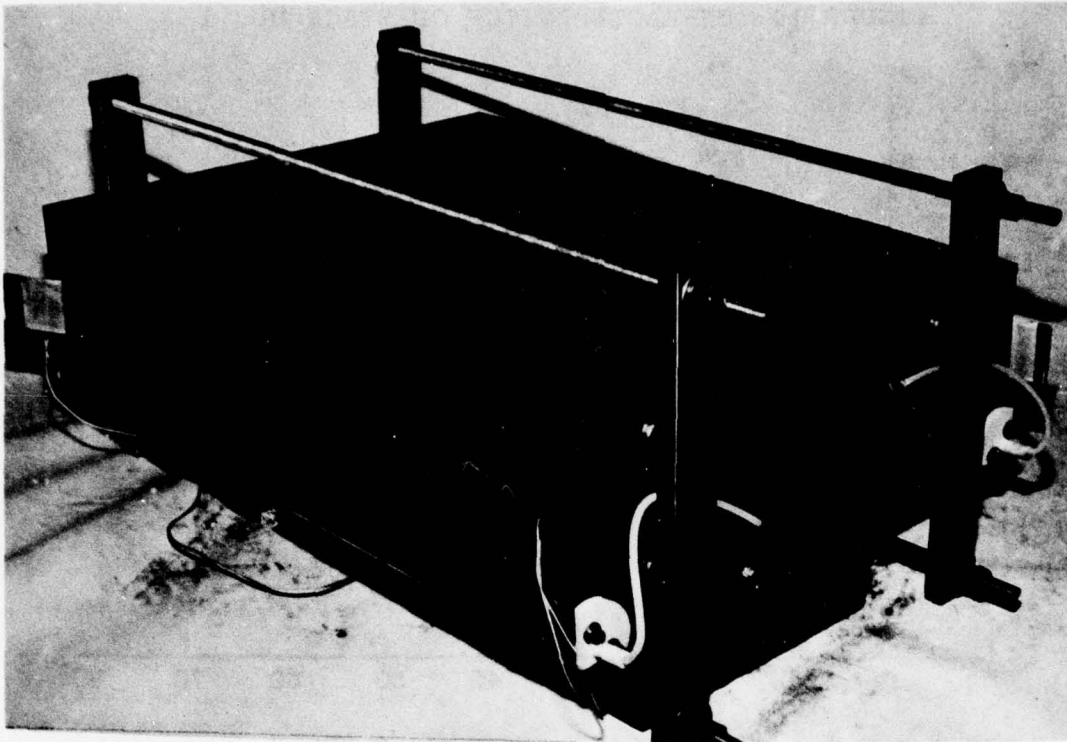


FIGURE 13 EIGHTY-CELL STACK

Variability of cell load potentials at 40 amperes load current was within the limits normally encountered with this cell design (+ 20 mV). Cell potentials were somewhat lower at the ends of the stack because of lower temperatures caused by heat loss thru the endplates.

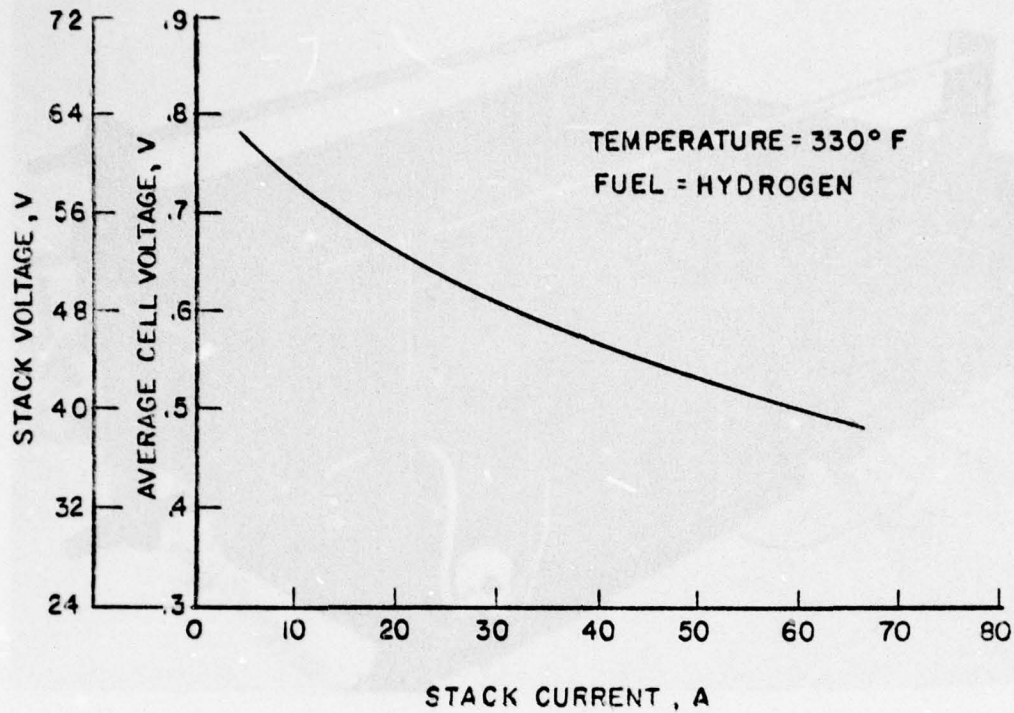
The generally lower cell voltages and wider variability encountered with Stack #2 was caused by poor stack compression as a result of an improperly dimensioned insulator plate. With Stack #3, some difficulties were encountered with gastightness following the initial performance tests, but this condition was corrected by repeating the electrolyte filling procedure.

Stack #5 was installed in the powerplant, and Stack #4 was supplied to MERADCOM together with other parts.

2.3.8 Stack Weight

The total weight of the 80-cell stack (excluding assembly auxiliaries) amounted to 49.35 lbs. A breakdown of the stack weight by component is shown in Table 4.

FIGURE 14 CHARACTERISTICS OF STACK NO. 1



DC039

FIGURE 15 CHARACTERISTICS OF STACK NO. 2

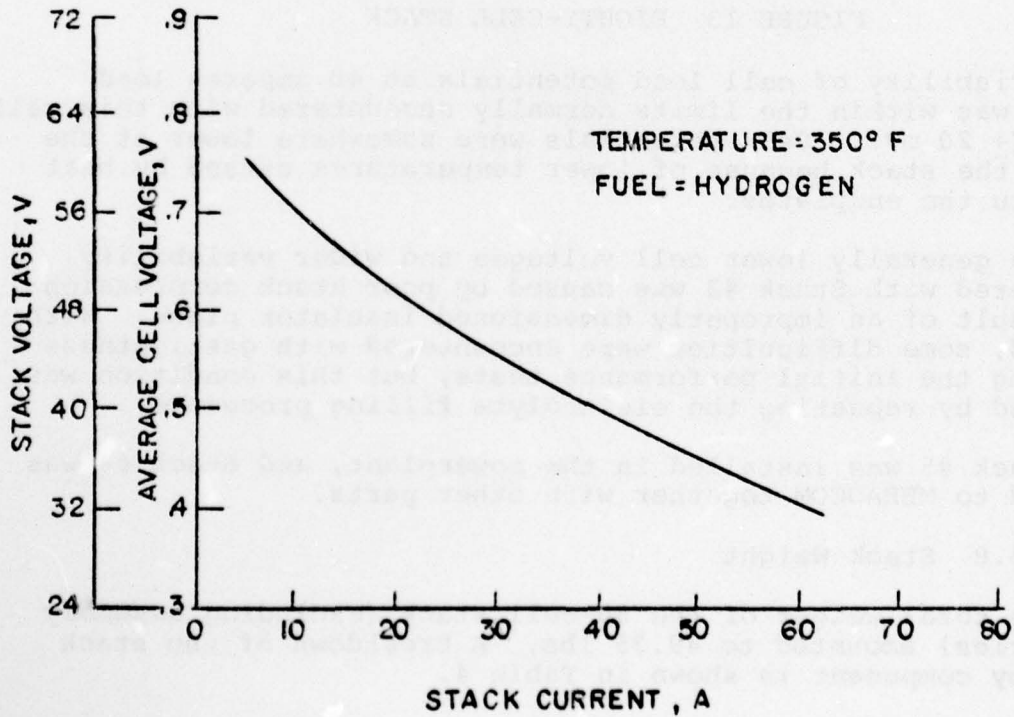


FIGURE 16 CHARACTERISTICS OF STACK NO. 3

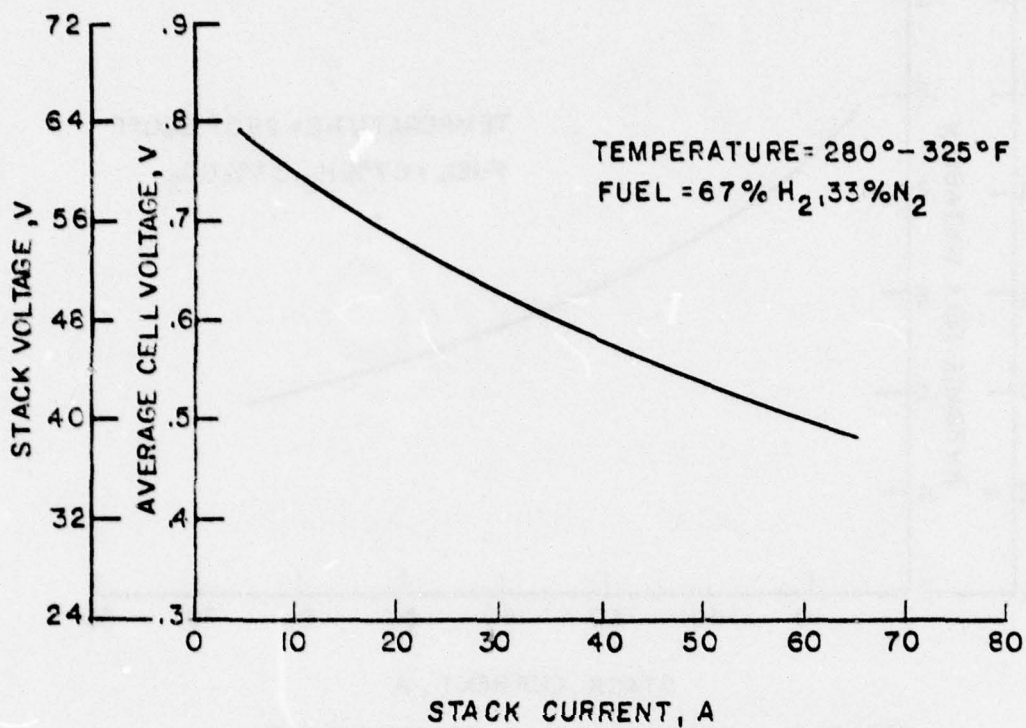


FIGURE 17 CHARACTERISTICS OF STACK NO. 4

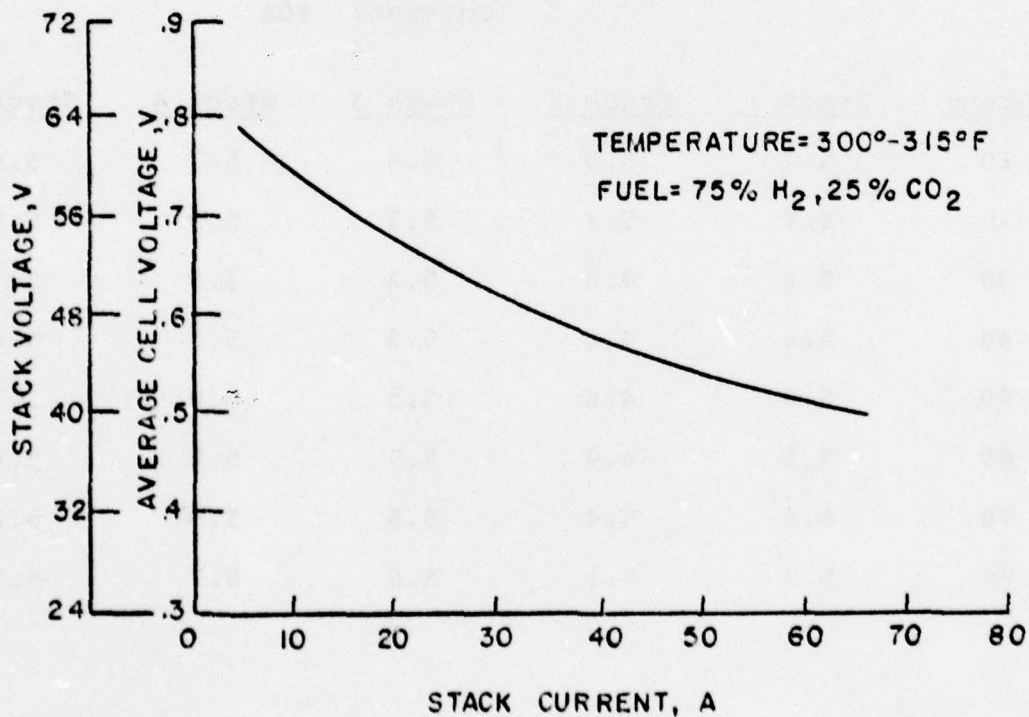


FIGURE 18 CHARACTERISTICS OF STACK NO. 5

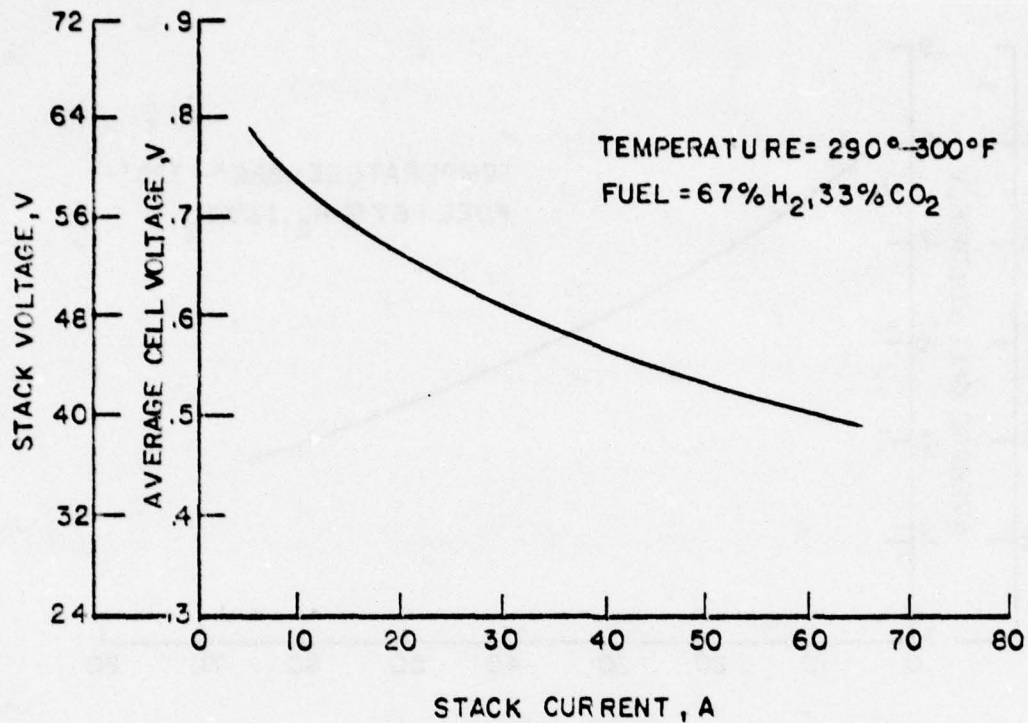


TABLE 2: STACK VOLTAGE MEASUREMENTS

Current: 40A

Cell Group	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5
1 - 10	5.1	5.0	5.4	5.7	5.4
11 - 20	5.4	5.4	5.3	5.9	5.8
21 - 30	5.6	4.8	5.3	5.5	5.7
31 - 40	5.6	4.8	5.5	5.7	5.6
41 - 50	5.6	4.8	5.5	5.8	5.7
51 - 60	5.5	4.9	5.5	5.8	5.8
61 - 70	5.4	5.4	5.5	5.9	5.8
71 - 80	5.3	5.1	5.6	5.7	5.7

TABLE 3
SINGLE CELL VOLTAGE MEASUREMENTS

Stack No. 5

Temperature 300°

Current: 40A

Fuel: 50% H₂, 50% CO₂

Cell No.	Voltage	Cell No.	Voltage	Cell No.	Voltage	Cell No.	Voltage
1	44	21	54	41	54	61	55
2	48	22	54	42	51	62	53
3	49	23	56	43	55	63	54
4	50	24	57	44	57	64	56
5	50	25	54	45	55	65	54
6	53	26	53	46	55	66	58
7	53	27	54	47	54	67	57
8	54	28	54	48	55	68	58
9	53	29	52	49	55	69	49
10	55	30	54	50	53	70	58
11	58	31	53	51	56	71	54
12	52	32	54	52	56	72	57
13	54	33	54	53	58	73	55
14	55	34	55	54	56	74	56
15	55	35	53	55	55	75	50
16	55	36	54	56	52	76	53
17	57	37	53	57	56	77	55
18	55	38	56	58	54	78	52
19	54	39	56	59	58	79	50
20	55	40	54	60	58	80	50

TABLE 4
STACK COMPONENT WEIGHT

	Unit Weight, Grams	Number	Weight, lbs
Bipolar Plates	215	81	38.31
Anodes	9	80	1.58
Cathodes	10	80	1.76
Matrices	8	80	1.41
Ta Inserts	2	160	0.70
Cement	4.5	80	0.79
Electrolyte	27	80	4.75
TFE Inserts	.15	160	0.05
TOTAL			49.35

Stack hardware contributed an additional 28.38 lbs. to the weight of the fuel cell subsystem. The major contributors to the hardware weight were the aluminum endplates (14.78 lbs.) and the tie bar-tie rod assemblies (10.03 lbs.).

Although an effort was made to use lightweight components to an extent consistent with the mechanical load requirements of the stack, no development of special lightweight stack assembly hardware components other than aluminum endplates was undertaken on this program. Some suggestions for reducing stack auxiliary hardware weight are presented in the recommendations section of this report.

A stack assembly auxiliary component weight breakdown is shown in Table 5.

TABLE 5
STACK ASSEMBLY HARDWARE WEIGHT

	<u>Unit Weight, Grams</u>	<u>Number</u>	<u>Weight, lbs</u>
Tie Bars	800	4	7.92
Tie Rods	240	4	2.11
Pressure Pads	45	8	.79
End Plates	3,360	2	14.78
Insulator Plates	350	2	1.54
Current Collectors	70	2	.31
Fill Ports	75	4	.66
Heaters	61	2	.27
		TOTAL	28.38

In addition to the stack assembly hardware, gas manifolding and ducting, as well as a heat exchanger and an air blower, are required to complete the fuel cell subsystem. A weight breakdown for these components is shown in Table 6. As in the case of the stack hardware, no special effort was expended toward reduction of the weight of these components.

TABLE 6
MANIFOLDING AND BLOWER WEIGHT

	Weight, lbs
Air Manifolds (2)	10.00
Fuel Manifolds (2)	5.00
Manifold Hardware	.92
Heat Exchanger and Blower	10.00
Air Ducts	2.50
TOTAL	29.42

2.4 Fuel Conditioner Subsystem

2.4.1 Description of Methanol Reformer

The methanol reformer converts a fuel mixture of 1.3 moles H_2O /1 mole CH_3OH to hydrogen, carbon dioxide, water vapor and a small amount of carbon monoxide for use in the fuel cell subsystem. The reformed gas composition on a dry basis is 70% hydrogen, 29.2% carbon dioxide, and 0.8% carbon monoxide. The reactor operates at a space velocity of 400 hr^{-1} for this product gas composition.

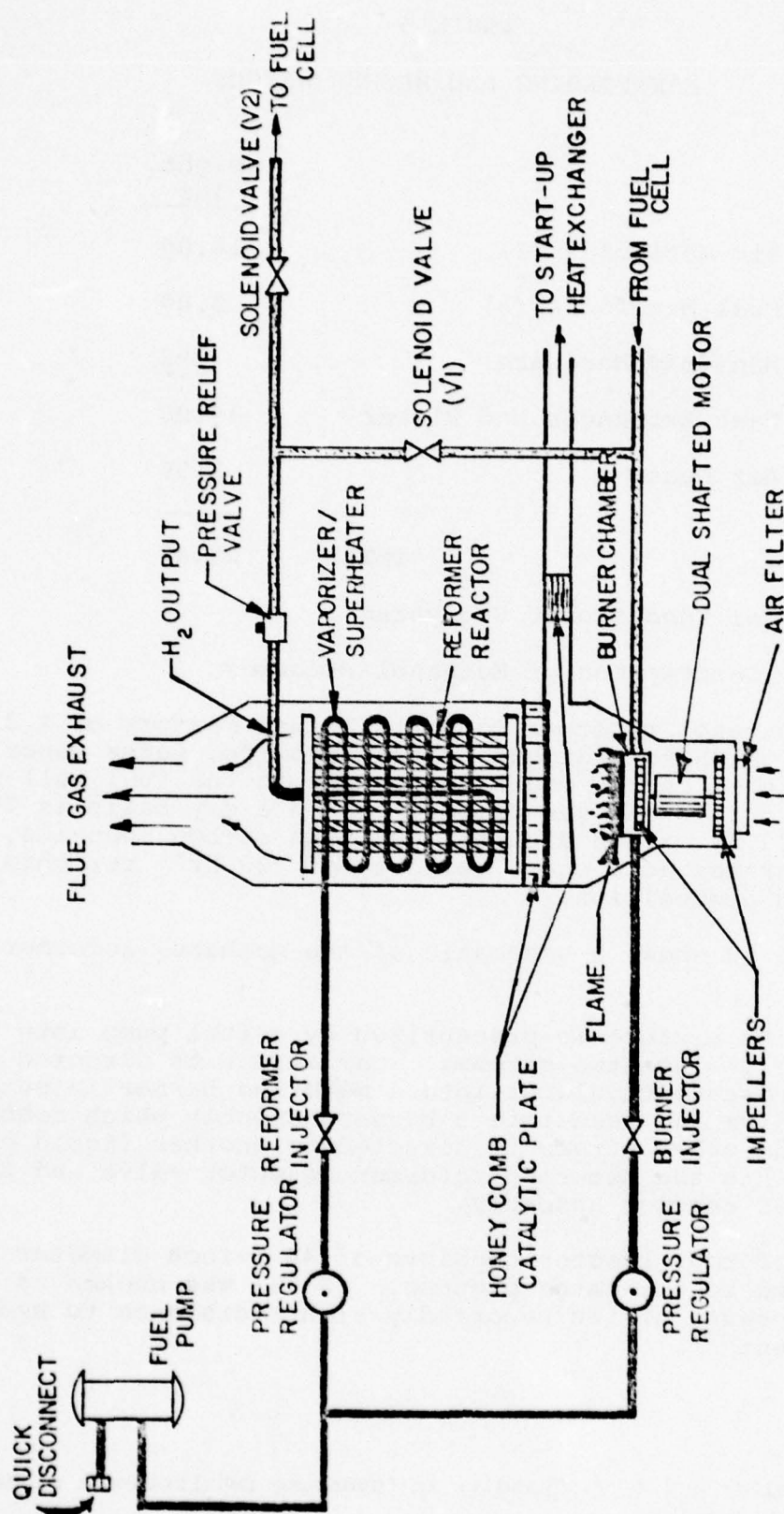
Figure 19 shows a schematic of the methanol reformer subsystem.

The feed mixture is pressurized by a fuel pump into the unit and then split into two streams. One stream is directed through a liquid pressure regulator into a metering burner injector solenoid valve and then into a burner assembly which combusts the liquid. The other stream is directed to another liquid pressure regulator into the metering reformer injector valve and then into the reformer reactor assembly.

The reformer reactor consists of 44 1-inch diameter SS-321 tubes welded to two large plenums. SS-321 was chosen as the material because of its reportedly high resistance to hydrogen embrittlement ⁽¹⁾.

(1) R. J. Walter and W. T. Chandler in "Hydrogen Embrittlement of Metals and its Control."

FIGURE 19 FUEL CONDITIONER SUBSYSTEM SCHEMATIC



The liquid first passes into a serpentine 1/2" diameter copper tube which allows heat transfer from the burner flue gas to the liquid for mixture vaporization. The vaporized fuel enters a 1" stainless steel tube, through a superheater box and exits from two 1" stainless steel tubes into a gas mixing plenum. This arrangement allows superheating of the fuel to approximately 300°F.

The superheated gas mixture disperses from this plenum into 8 1" diameter SS tubes, filled with Girdler Chemicals Inc., T 2130 copper/zinc catalyst crushed to 1/2 of its original 1/8" x 1/4" pellet size. The crushing provides more catalyst surface area for the endothermic reforming reaction. In the presence of the catalyst, the vaporized water and methanol react at an average temperature of 390° to form hydrogen and oxides of carbon. The methanol and water react throughout the reformer flowing in a series-parallel arrangement. The volume of catalyst used is 450 in³, and its weight is approximately 22 lbs.

The output from the reformer is directed to either the fuel cell intake manifold or to the burner assembly to be combusted directly. The direction of hydrogen is determined by powerplant requirements at this point of operation. The gases are routed by the use of two two-way large orifice solenoid valves (V1 and V2).

During fuel cell operation, hydrogen not utilized by the stack flows to the burner assembly via valve V1 to augment the heat input requirement of the endothermic reforming reaction.

The burner assembly is shown in Figure 20. It includes a

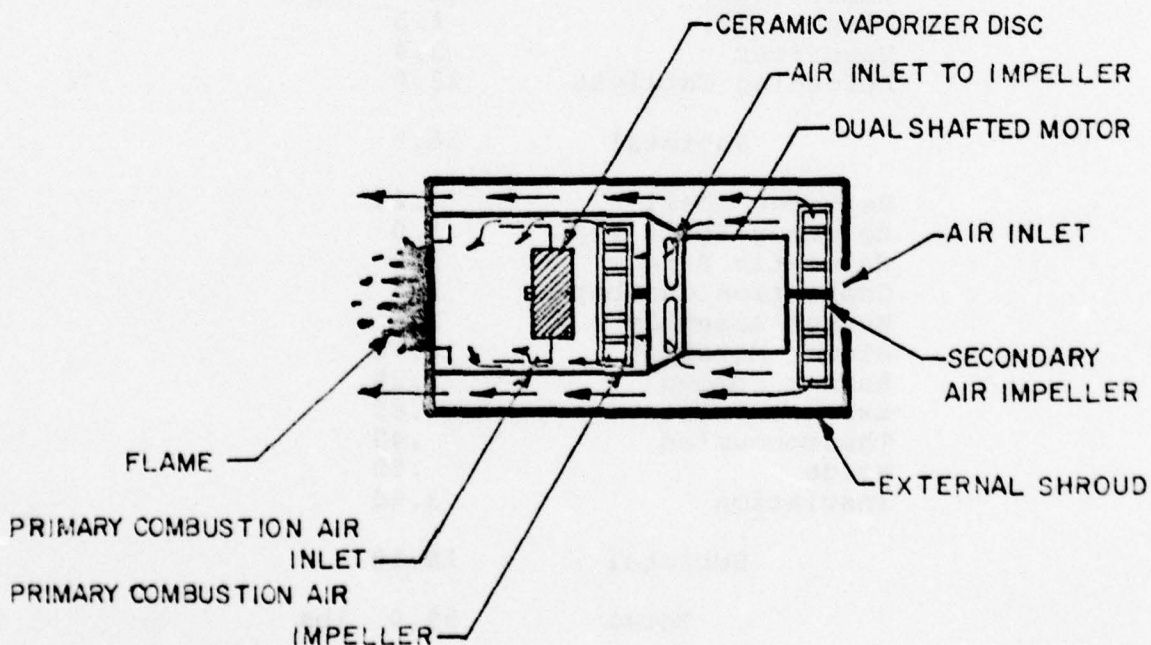


FIGURE 20 BURNER ASSEMBLY

dual-shafted blower motor with impellers, a burner chamber, vaporizer stone and a glow plug. The blower supplies ambient air for combustion and also directs the hot flue gases over the reformer reactor tubes in a two pass configuration.

During the start-up mode, the flue gas is ducted to a start-up heat exchanger used to warm the fuel cell to operating temperature. A solenoid operated damper is used to direct this gas to the heat exchanger. It is controlled by stack temperature (T3).

Downstream of the burner assembly is a honeycomb catalytic plate. It is used to complete combustion of unburned products from either the liquid feed to the burner or spent fuel gases exhausted from the fuel cell anode. This plate is also included in the start-up heat exchanger duct.

There are various temperature sensors throughout the reformer subsystem. They are used to control the operation of the powerplant. Their use is explained in the Control Logic section.

The entire reformer subsystem weighs 55 lbs and encompasses a volume of 1.1 ft³. (See Table 7.) It is completely insulated from other components in the powerplant.

TABLE 7
REFORMER WEIGHT

Tubes (44)	11	lbs
Plenums (2)	1.5	
Vaporizer	2.4	
Reforming Catalyst	22.0	
Subtotal	36.9	
Reformer Shell	3.20	
Reformer Shell Top	1.0	
Catalytic Burner	1.0	
Combustion Chamber	1.5	
Burner Assembly	2.1	
Blower Motor	2.75	
Burner Shroud	1.25	
Exhaust Duct	.85	
Thermocoupled	.45	
Welds	.50	
Insulation	3.50	
Subtotal	18.10	
Total	55.0	lbs

2.4.2 Reformer Development

Work on powerplant component development began with design, construction, and testing of a sub-scale hydrogen generator. Initial efforts were directed at catalyst selection and optimum geometric reformer design.

The gross output needed from the fuel cell is the determining factor in the sizing of the reformer.

An estimated output of 2 kW from the fuel cell at a minimum voltage of 36 volts was used as the controlling parameter. This means a maximum current of 61 amperes. To produce 61A in an 80 cell stack at 100% fuel utilization would require 1.2 ft³/min. of hydrogen. With these calculations as a basis, a test reactor unit of approximately one-quarter capacity of the full 1.5kW system size was designed and fabricated. The reactor was a cylindrical unit 13 inches long and 2 inches in diameter. A special, easily removable end cap was made for one end to facilitate quick changing of the catalyst. The tube included a gas mixing plenum at each end. The test reactor is shown in Figure 21.

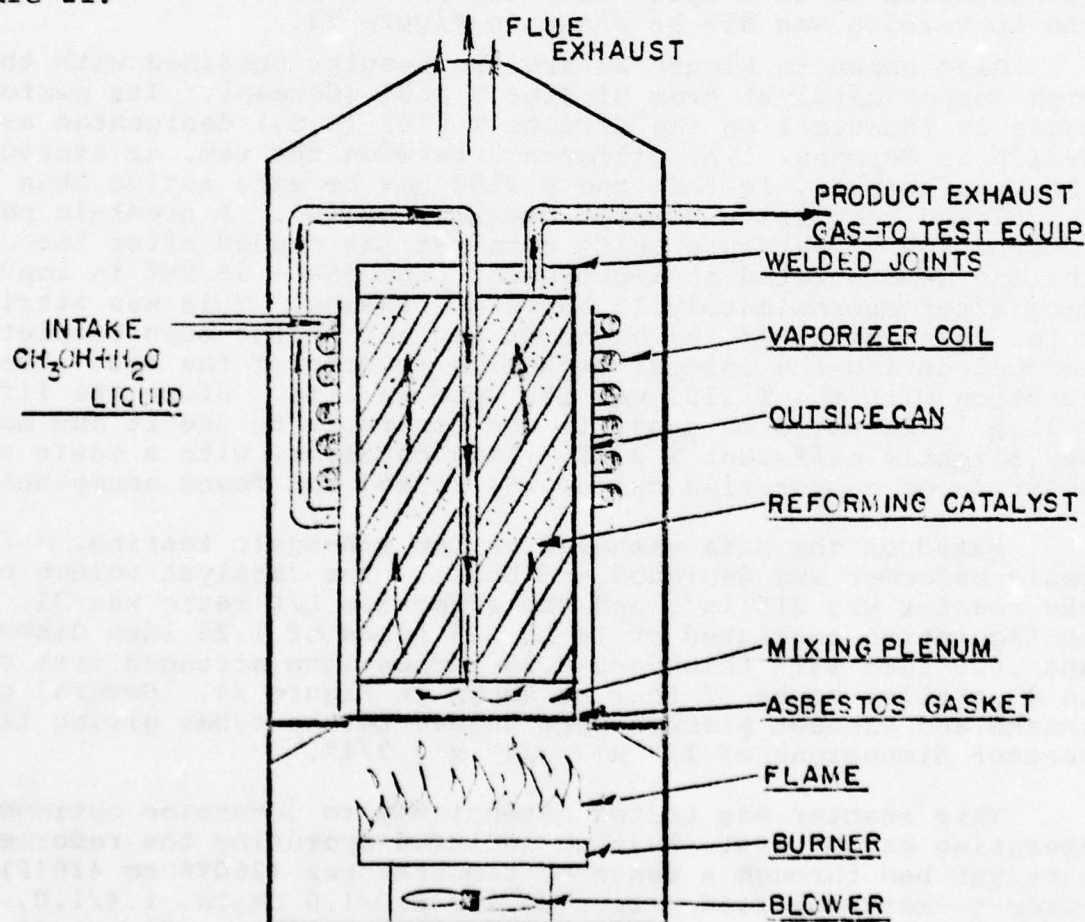


FIGURE 21 TEST REACTOR

The first test of this methanol steam reformer yielded poor methanol conversion as seen in Figure 22. This may have been due to the size of the catalyst pellets ($1/8"$ x $1/4"$ diameter) and the geometric shape of the reactor employed.

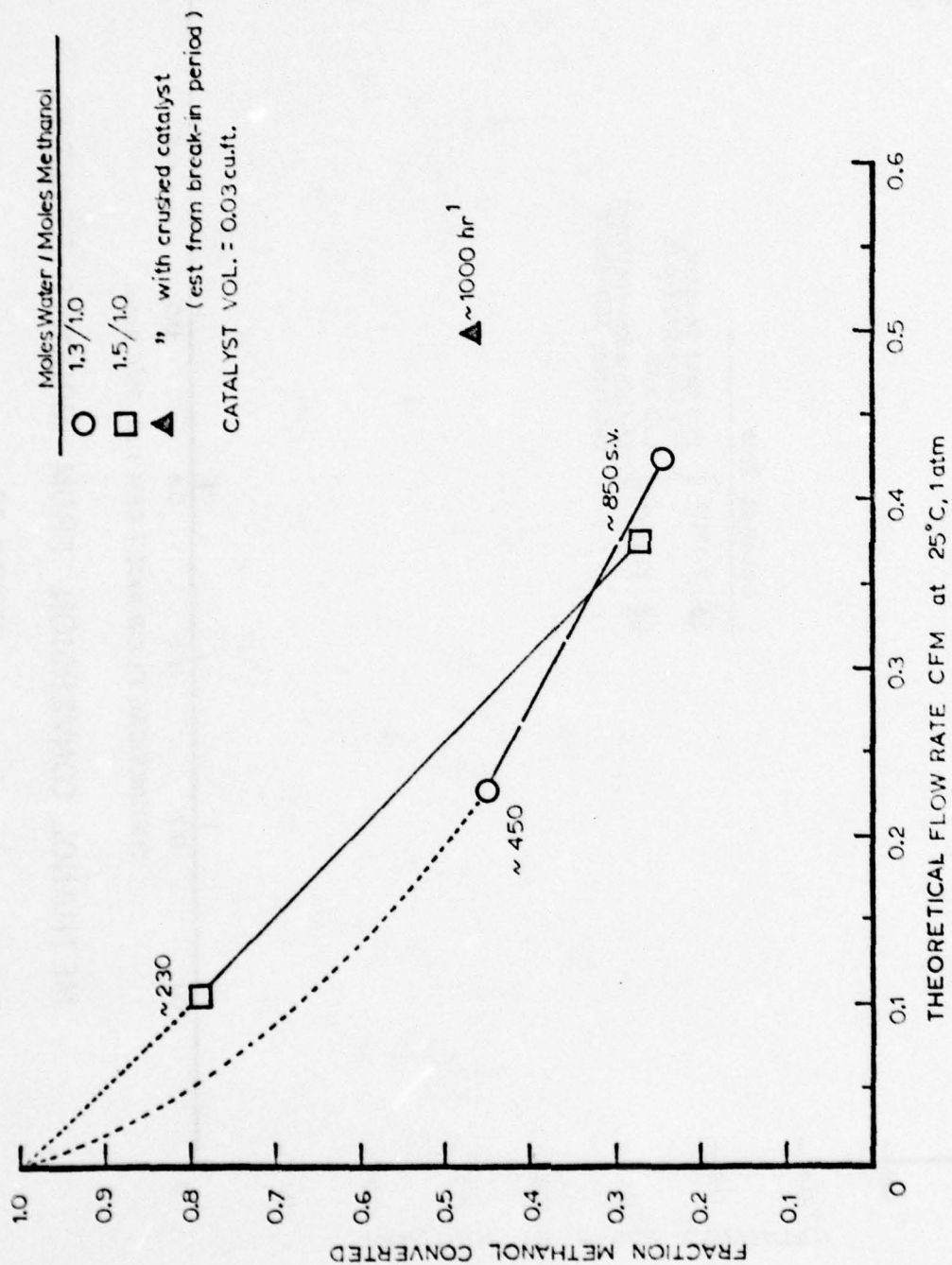
In order to evaluate these factors, the catalyst was crushed to approximately $1/2$ to $1/3$ of the original pellet size. This technique was employed after discussing the manufacturing of the catalyst pellets with Girdler Chemicals, Inc. The vendor assured the homogeneity of the pellets thus the increased exposed surface area of the catalyst had a positive effect on the methanol conversion. Also, the reactor was redesigned to increase the L/D ratio. The internal catalyst volume was kept constant at 0.03 ft^3 as in the previous reactor, but the L/D was increased from 4 to 18.4. The reactor consisted of 4 $1.25"$ diameter stainless steel tubes welded into a "W" configuration which would fit in a 4 inch square box, 11.5 inches high.

The conversion performance with this reactor improved greatly over the first unit. This design probably reduced channeling effects. Complete conversion of the methanol feed was achieved up to a space velocity of 867 hr^{-1} . At 1022 hr^{-1} , the conversion was 85% as shown in Figure 23.

Also shown in Figure 23 are the results obtained with the high copper catalyst from Girdler T 2107 (German). Its performance is identical to the Girdler T 1707 (U.S.) designated as T-2130 in Germany. The difference between the two, as stated by the manufacturer, is that the T 2107 may be more active than T 1707 and requires a shorter break-in period. A break-in period for the low temperature shift catalyst was needed after lab testing demonstrated an improvement from 85% \rightarrow 99.99% in conversion after approximately 12 hours of running. This was attributed to sections of the catalyst bed not having been completely reduced during the initial reduction process of the bed. The question with the T 2107 was its unknown life. Since the life of T-2130 is known to be good, it was desirable to use it and not the slightly different T 2107. This catalyst, with a basic composition of copper/zinc oxide, was tested and found acceptable.

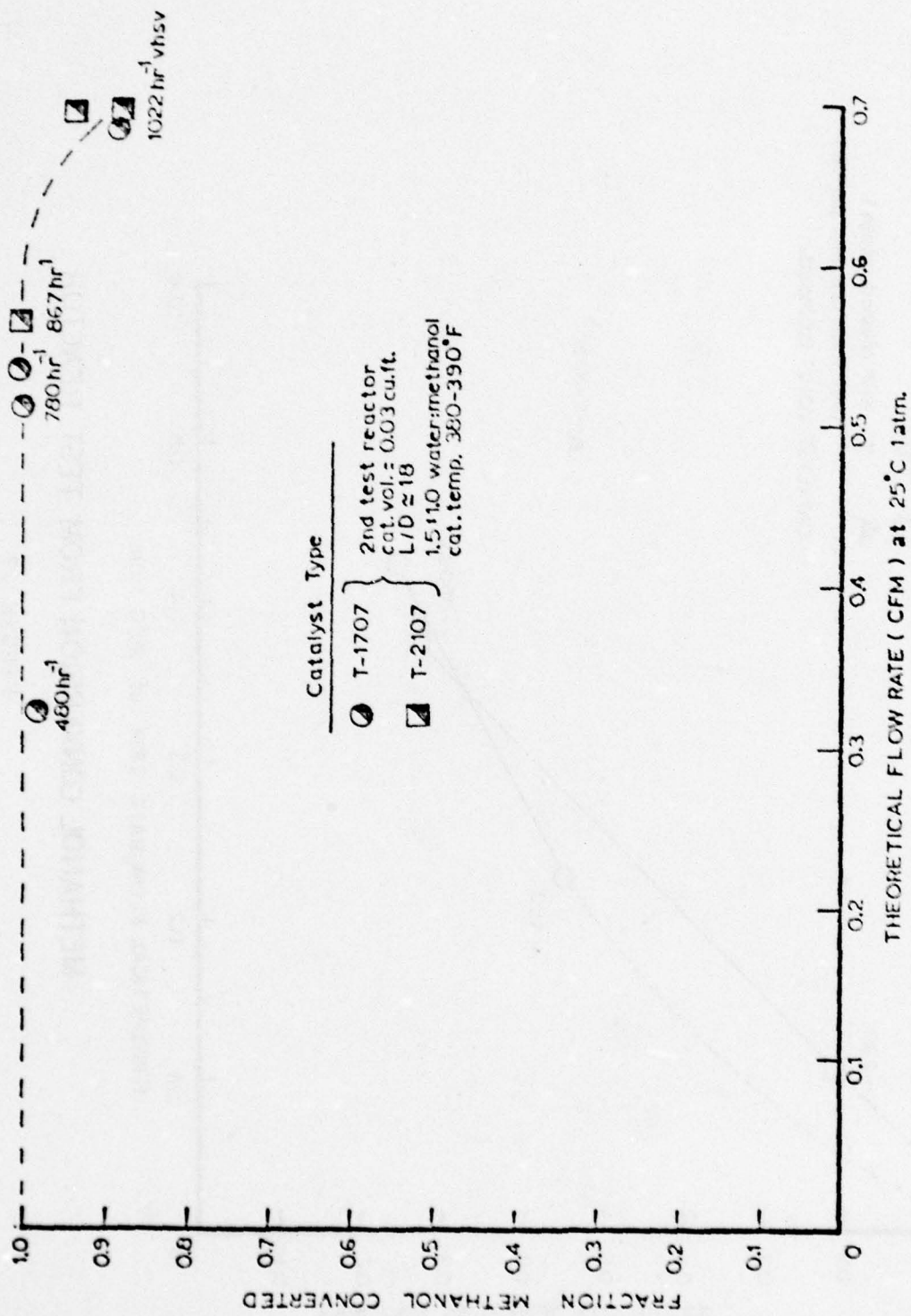
Based on the data gathered on the sub-scale testing, a full scale reformer was designed and built. The catalyst volume of the reactor was 215 in^3 , and the effective L/D ratio was 31. Its configuration consisted of 16 SS 316 tubes of 1.25 inch diameter and $.020$ inch wall thickness 9.25 inches long arranged vertically in 4 parallel banks of four as shown in Figure 24. Several gas intake and exhaust plenums were welded to the tubes giving final reactor dimensions of $11" \times 7 \frac{3}{4}" \times 7 \frac{3}{4}"$.

This reactor was tested extensively to determine optimum operating parameters. Testing included operating the reformer catalyst bed through a range of temperatures (360°F to 420°F) and water-to-methanol feed ratios of $1.3 \text{ H}_2\text{O}/1.0 \text{ CH}_3\text{OH}$, $1.4/1.0$, and $1.5/1.0$. The results of this testing are shown in Figure 25.



METHANOL CONVERSION FROM TEST REACTOR

FIGURE 22



METHANOL CONVERSION FROM IMPROVED REACTOR

FIGURE 23

CATALYST VOLUME = 215 CU. IN.
EST. REACTOR WGT. = 11 POUNDS

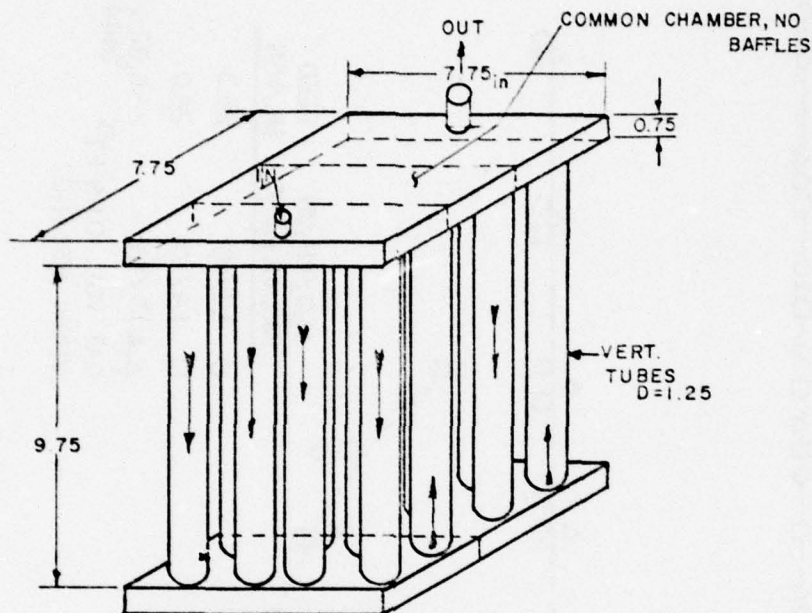


FIGURE 24

16 TUBE REACTOR SECTION

The 1.3/1 water to methanol ratio was chosen for further work because of the lower water burden content. An operating temperature of 380°F was chosen for the catalyst bed. This allows a high conversion of methanol with low CO concentration in the product.

This design was incorporated in the breadboard model of the 1.5kW generator. Subsequent testing of the breadboard system validated this reactor at steady state conditions. The product gas composition on a dry basis analyzed by infrared absorption was 72.5% hydrogen, 26.8% carbon dioxide and .7% carbon monoxide. This composition test was carried out with a V.H.S.V. (Volume of Hydrogen Space Velocity) of approximately 400 hr⁻¹.

$$\text{V.H.S.V.} = \frac{\text{Volume of H}_2 \text{ produced/hr}}{\text{Volume of Catalyst in Reactor Bed}}$$

This represents a H₂ production rate of .83 ft³/min. Further tests of this reformer demonstrated a maximum output of 1.25 ft³/min of hydrogen. This is enough fuel for an output of 58 amperes in an 80 cell stack at a utilization of 100% by the fuel cell stack. During breadboard testing, the limitations of this reformer became apparent. The fuel cell stack incorporated

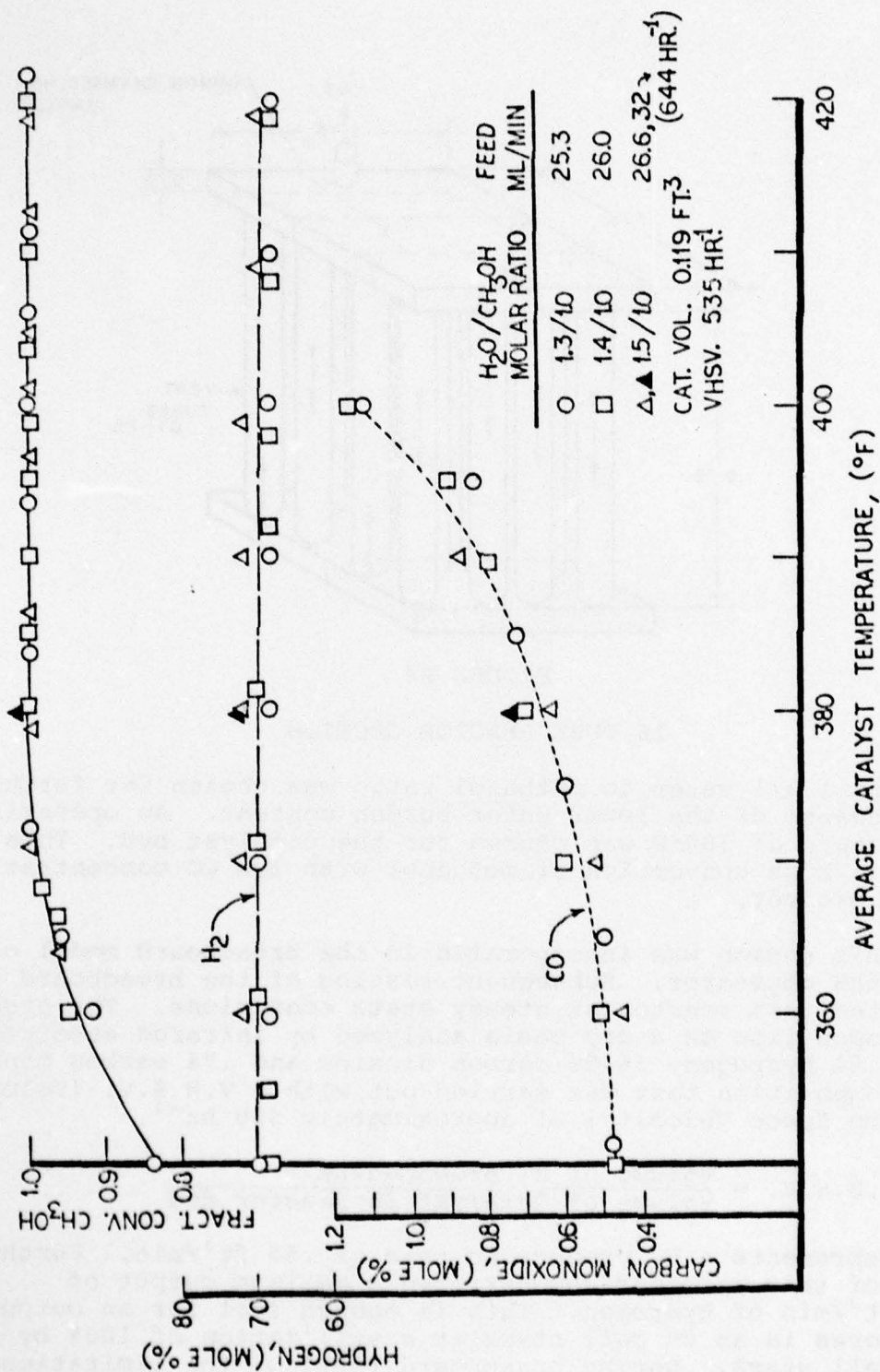


FIGURE 25

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in the system required 20-30% excess of hydrogen over the operational load range. Also during load response testing the reformer exhibited marginal response characteristics. Relatively long periods of time, e.g. 2 to 3 minutes, were required to vaporize/superheat and process the methanol-water mixture into the H₂ rich product stream.

It appeared from the above that an increase of reformer volume would also increase its heat capacity, providing a heat source for coping with large increases in feed rates. In addition, the advantage of a larger reformer would be to keep the operating space velocity between 400-500 hr⁻¹ at full powerplant loads with fuel cell stack utilization as low as 60% (40% excess fuel).

2.4.3 Reformer Performance

A new reformer was designed and fabricated with a catalyst volume of 450 in³. It consisted of 44 one inch diameter tubes with gas-mixing plenums welded to each end of the tubes. The design included a built-in vaporizer/superheater in the first bank of the catalyst tubes. The overall dimensions of the reformer were 14 3/8" x 9 1/2" x 6 7/8". This reformer design is shown in Figure 26.

The reformer was put on test at feed rates as high as 47.5 ml/min of water-methanol mixture. This represents a production of 1.86 ft³/min of hydrogen at a V.H.S.V. of 430 hr⁻¹. This reformer was found to be able to supply sufficient fuel to the stack following load increases meaning greater than 15cc/min in liquid feed rate to the reactor (see response testing of the breadboard system).

A problem developed during the testing in that the stainless steel 3-tube and box vaporizer/superheater could not heat the liquid fuel to superheat temperature at 28cc/min and above. Additional lengths of copper tubing were installed in series with the 3-tube and box vaporizer. The increased heat transfer area enabled the liquid fuel to be superheated to 300°F with flowrates to 47cc/min of methanol-water mix. This design was incorporated in the final powerplant design.

2.5 Automatic Control Unit

The 1.5kW methanol powerplant was designed for unattended automatic operation. An automatic control unit (ACU) was developed and tested for ability to provide automatic control of the following powerplant functions:

- (1) Start up of the powerplant
- (2) Fuel feed rate regulation with output load
- (3) Temperature control for the fuel conditioner subsystem
- (4) Shutdown of the powerplant

The functional block diagram of the ACU is shown in Figure 27.

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FIGURE 26

44-TUBE REFORMER

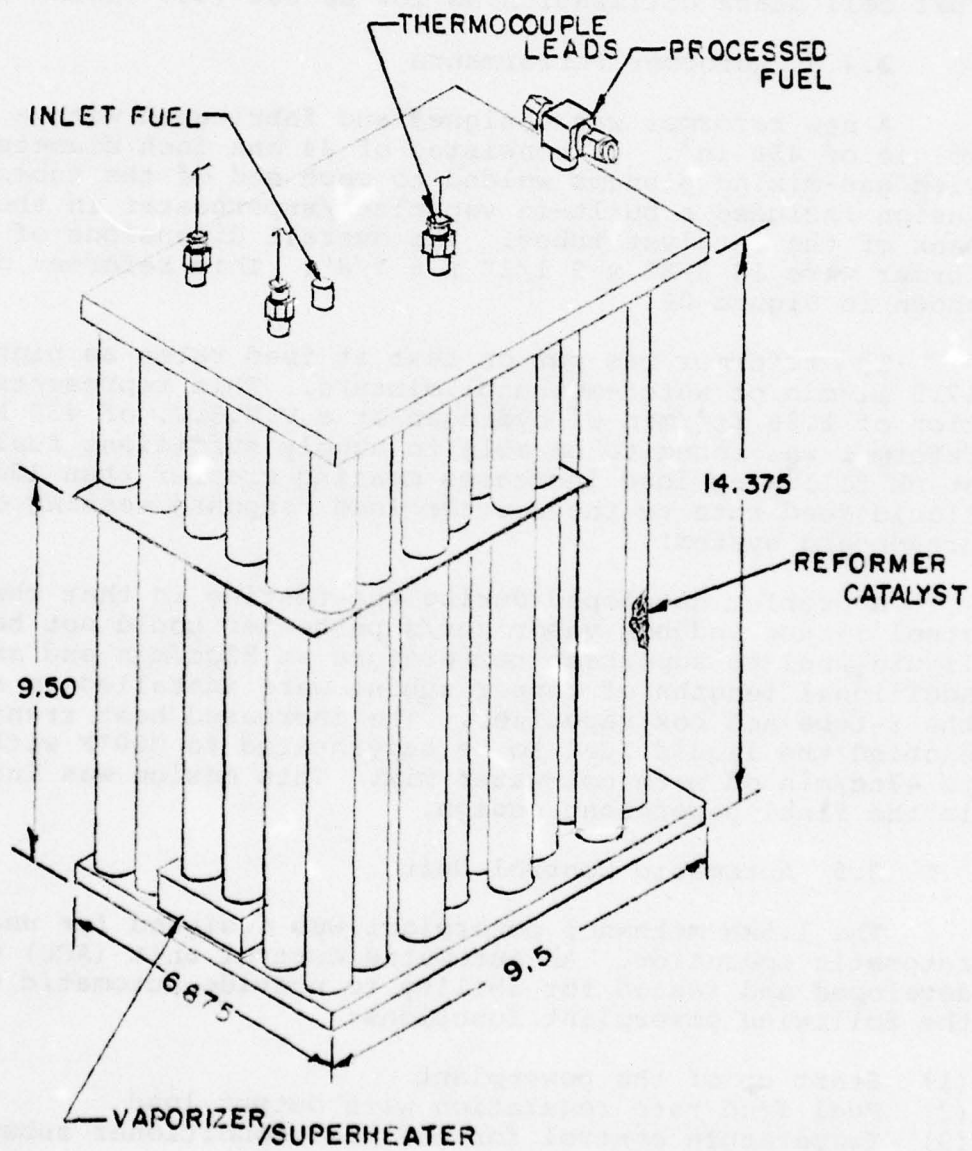
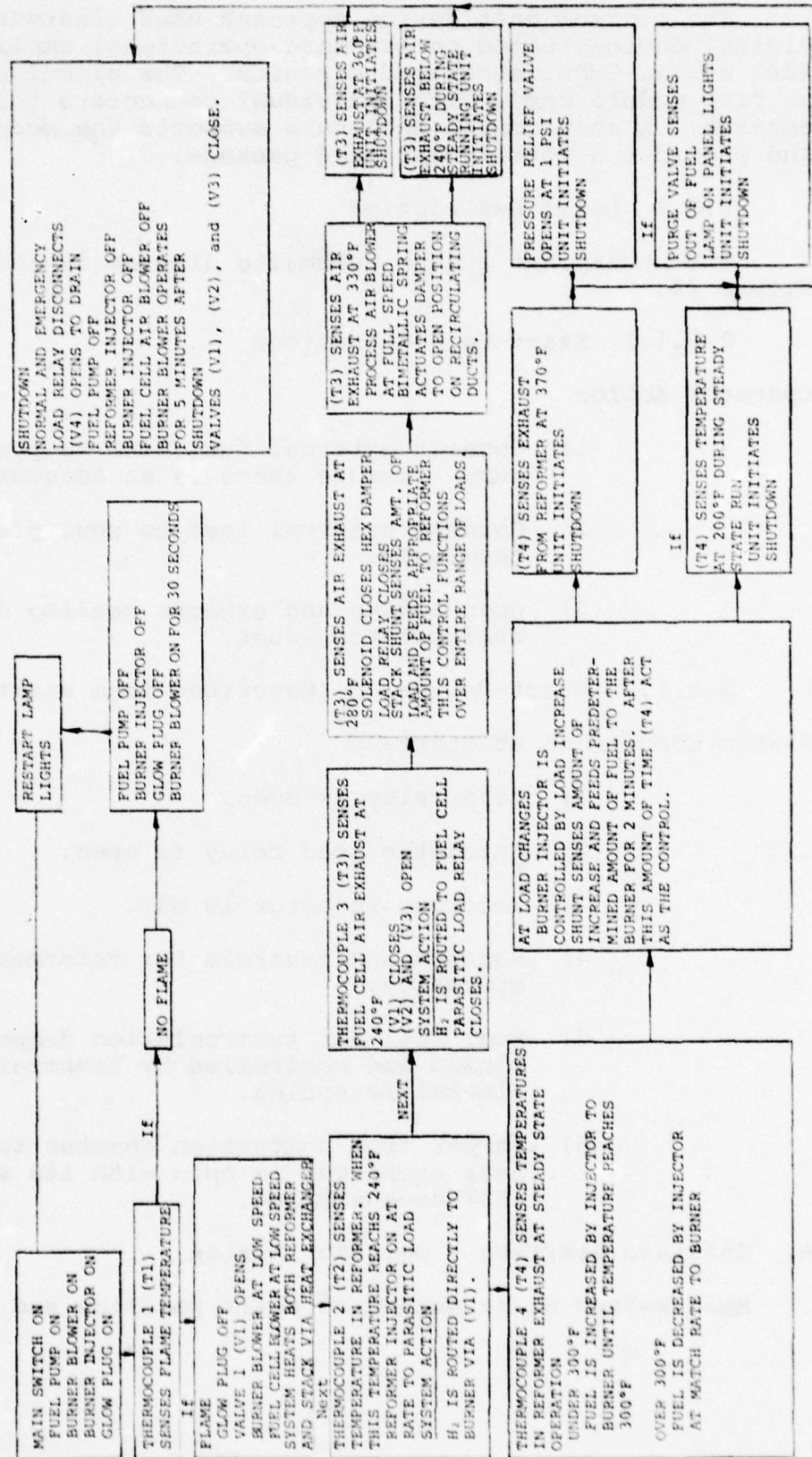


FIGURE 27
CONTROL LOGIC DIAGRAM



The control unit design approach uses discrete analog and digital devices based on standard operational amplifiers and 4000 series CMOS integrated circuits. The circuitry is mounted on five module cards with individual connectors for ease of service. A sheet metal enclosure supports the module connectors and provides a totally enclosed package.

2.5.1 Logic Description

The powerplant system schematic diagram is shown in Figure 28.

2.5.1.1 Start-Up Preparations

Operator Action

- 1) Connect external fuel line to powerplant fuel pump. Insure there is an adequate fuel supply.
- 2) Connect external load to powerplant output terminals.
- 3) Open intake and exhaust sealing dampers on recirculating duct.

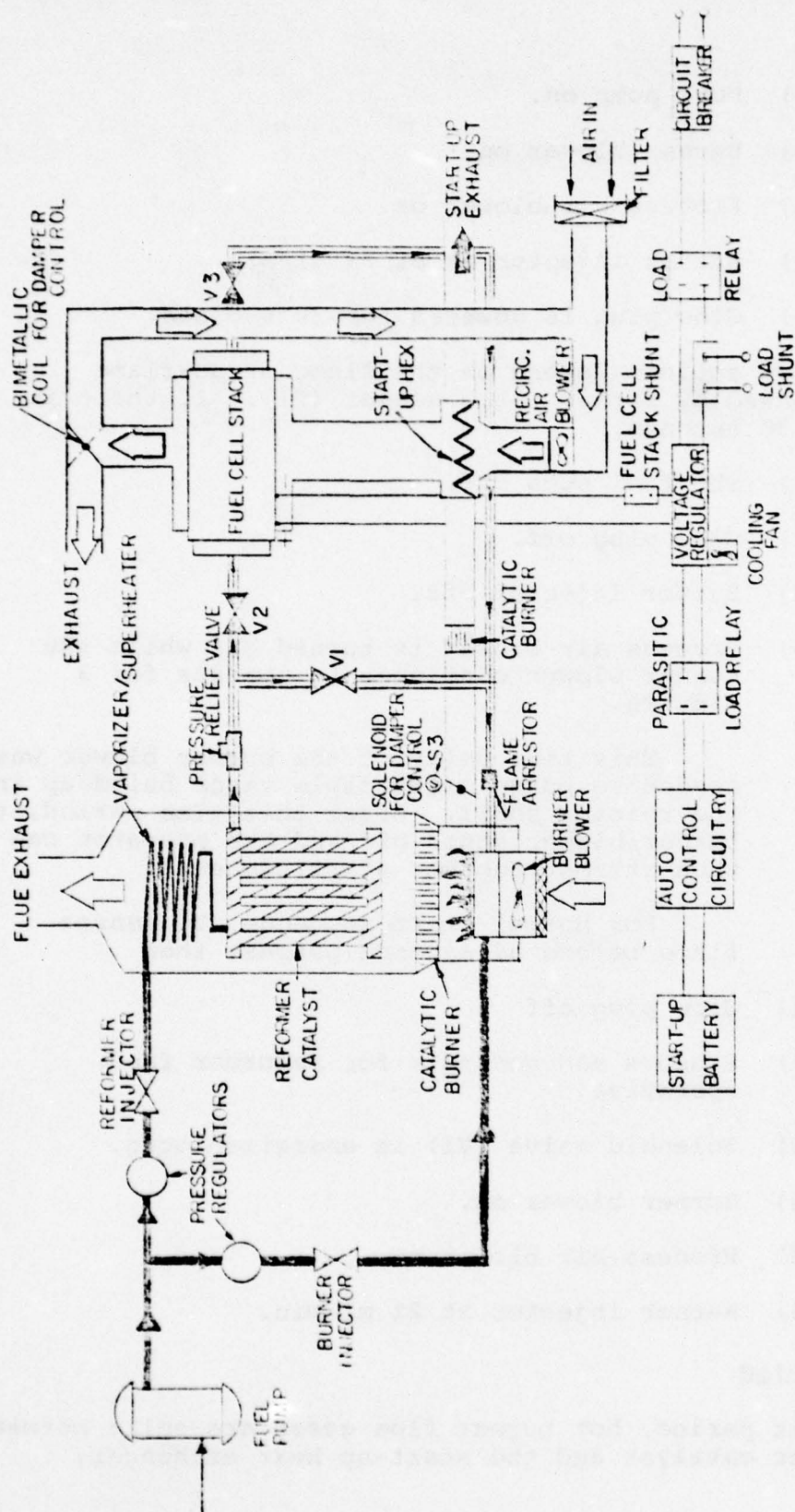
2.5.1.2 Start-Up Period (Described from start to idle)

System Conditions at Start-Up

- 1) Load relay is open.
- 2) Parasitic load relay is open.
- 3) Reformer injector is off.
- 4) Sensors and controls for reformer feed in-operative.
- 5) Fuel cell air recirculation damper positioned closed and controlled by temperature sensing bimetallic spring.
- 6) Damper from combustion chamber to start-up heat exchanger is open with its solenoid (S3) de-energized.

A. Initiate Start-Up - Operator Action

Main switch S1 is pushed to start position and released.



15 KW POWERPLANT SCHEMATIC FIG. 28

System Action

- 1) Fuel pump on.
- 2) Burner blower on.
- 3) Process air blower on.
- 4) Burner injector on at 23 ml/min.
- 5) Glow plug is powered for 30 seconds.

These system actions depend on the flame or no-flame situation as sensed by burner flame sensor (T1). If there is no flame after 30 seconds,

- 1) The fuel pump off.
- 2) Glow plug off.
- 3) Burner injector off.
- 4) Process air blower is turned off while the burner blower continues to operate for 3 minutes.

This time delay of the burner blower was needed to purge combustible vapor build-up in the reactor shell. After this time period, the burner blower shuts off and the operator can then attempt another start sequence.

For normal start sequence, T1 senses flame before 30 seconds passes; then

- 1) Glow plug off
- 2) Sensors and controls for reformer feed operative.
- 3) Solenoid valve (V1) is energized open.
- 4) Burner blower on.
- 5) Process air blower on.
- 6) Burner injector at 21 ml/min.

B. Warm-Up Period

In this period, hot burner flue gases are split between the reformer catalyst and the start-up heat exchanger.

The damper to the heat exchanger is opened at start-up, since solenoid S3 is kept de-energized.

When the stack air out reaches 280°F, T3 signals the heat exchanger damper to close by means of a solenoid (S3).

The next system action occurs when the reformer exhaust temperature reaches 200°F as sensed by T4. Lab experience has shown that this temperature is indicative of an average reformer temperature of 250°F, which is hot enough to begin hydrogen production. At T4 sensing 200°F, the reformer injector pumps 7 ml/min to the reactor, enough to support parasitic load requirements. Since the fuel cell stack takes longer to heat up than the reformer, the initial hydrogen produced is routed to the burner.

The burner injector is now controlled by reformer exhaust temperature T4. When it reaches 260°F, the burner injector decreases to 15 cc/min from the start-up rate. It further reduces to a bleed rate of 10 cc/min when T4 reaches 310°F.

Next system action occurs when the stack air out reaches 200°F as sensed by T3. This signals V1 to close while opening V2 and V3, thereby routing hydrogen through the fuel cell. These valves (V1, V2, and V3) are normally closed 2-way solenoid valves. These were chosen because it was felt that the reactor would be protected from oxidation in case of both fuel cell and battery power failure. The hydrogen is allowed to purge the fuel cell for 30 seconds via a timer circuit. After this time period, the parasitic load relay closes and the powerplant begins to operate on its own power; that is, all electrical components are switched off of battery power and run by the powerplant. Also, the unit begins recharging the start-up battery directly from the fuel cell power.

C. Ready for Load

System Conditions

- 1) Reformer exhaust temperature (T4) at 300°F.
- 2) Fuel cell air exhaust temperature (T3) at 250°F.
- 3) Parasitic-relay is closed.
System is ready to assume external load.

At fuel cell air exhaust of 250°F the load relay closes, and assumes the external load.

2.5.1.3 System Responses

A. Idle to Full Load

When reformer exhaust (T4) and fuel cell stack exhaust (T3) temperatures reach 300°F and 250°F respectively, the load relay closes and assumes the external load. Simultaneously, the voltage regulator cooling fan is powered on.

The reformer injector is controlled by a shunt on the fuel cell stack. Upon load increases the shunt signals the reformer injector to increase liquid fuel flow to 38 ml/min for 100 seconds to the reactor. After this time period, the injector decreases flow to the amount required by the load at 65% stack utilization.

The burner injector is controlled by reformer exhaust temperature (T4) at steady state conditions. During load increases sensed by the load shunt, the burner injector increases to its maximum 23 ml/min for 100 seconds. After this time period, the injector is again controlled by the reformer exhaust temperature (T4).

B. Idle to Part Load

The system, that is burner and reformer injectors, responds in the same manner, as stated above in A, if the load increase is 10 amps or above. If the increase is below 10 amps the reformer injector increases flow corresponding to the load applied, and the burner injector remains controlled by the reformer exhaust temperature.

C. Full Load to Idle

Operator removes load, the system action is reformer injector reduces input into reactor to 7 ml/min and burner injector is controlled solely by reformer exhaust temperature (T4). If the stack air exhaust (T3) falls below 280°F, the solenoid (S3) controlled heat exchanger damper is de-energized to the open position, providing make-up heat to the stack.

D. Full Load to Part Load

Reformer injector reduces flow to rate matching load on the stack, and the burner injector controlled by T4.

E. Part Load to Full Load

Reformer injector controlled by load shunt increases flow as stated above in Section A if the load increase is 10 amps or above. If the load increase is below 10 amps the reformer injector increases to amount corresponding to the load imposed. Burner injector is controlled as stated above.

F. Part Load to Idle

Reformer injector decreases amount of fuel to idle rate 7 ml/min. Burner injector is controlled by T4.

2.5.1.4 Shutdown

Initiated by operator or by system itself with an out of range parameter.

A. Normal Shutdown - Operator Action

Operator activates main switch (S1) to off and releases.

- 1) Load relay disconnects.
- 2) Parasitic load relay disconnects.
- 3) Fuel pump off.
- 4) Process air blower off.
- 5) Burner injector off.
- 6) Reformer injector off.
- 7) Voltage regulator cooling fan off.
- 8) Burner blower runs for 3 minutes, then off.
- 9) Valves V2 and V3 are energized for 3 minutes, then closed.

B. Emergency Shutdown

A multitude of conditions will initiate automatic system shutdown. The major out of range parameters are presented below.

- 1) Uncontrollable temperature of
Fuel cell going too high > 360°F as sensed
by T3.
Fuel cell going too low - not hot enough to
support load imposed.
Fuel cell temperature going too high or low
could be caused from
 - a) Fuel cell damper bi-metallic spring jams
during operation.
 - b) Solenoid controlling heat exchanger damper
fails.

Average reformer catalyst too high
> 350°F as
sensed by

Average reformer catalyst too low - hydrogen
production
is too low to
support load on
stack

- 2) External dead short - circuit breaker opens, unit adjusts to idle.
- 3) Internal short - stack current will try to rise, this is sensed, opening load relay, system goes to shutdown.
- 4) Hydrogen product valves V1, V2, or V3 close during operation. The fuel cell voltage falls because of lack of hydrogen and unit goes to shutdown. If pressure builds up in system to above 1 psi, a pressure relief valve pops open protecting the system.
- 5) Voltage from fuel cell too low for any reason - unit initiates shutdown.

These reasons could be

- a) Loss of burner flame - subsequent drop in hydrogen production causes low voltage.
- b) Out of fuel situation.
- c) Rupture in vaporizer tube.
- d) Rupture in reformer tube.
- e) Reversed cells in fuel cell stack.
- f) Process air blower failure.
- g) Rupture in recirculating duct - stack not able to maintain temperature.
- h) S3 fails to open heat exchanger damper - stack too cold to support load.
- i) Filter on either blower or process air blower become clogged. Situation would be flame out or insufficient oxygen to the fuel cell stack.

- j) Burner or reformer injector failure.
- k) Fuel pump failure.
- l) Regulators become plugged.
- 6) Load relay failure - unit fails to respond to load imposed and initiates shutdown.
- 7) Shunt failure - unit would sense open circuit reading on ammeter and shut down.
- 8) Thermocouple failure would send signal of no voltage to automatic controls. This would say temperature is too low and initiate shutdown.
- 9) RTD failure would send a maximum voltage signal to automatic controls initiating shutdown.

2.5.2 Circuit Functional Description

The circuit schematic diagrams are shown in Figures 29 thru 33.

2.5.2.1 Start Up and Ignition Sequence

When the main switch is pushed to the start position: (Figure 33).

- A. The fuel pump is started to provide fuel to the system.
- B. The ignition glow plug is energized by relay K4.
- C. The green ON lamp is energized.
- D. A 30 second start up timer is energized. If burner flame is not sensed at the end of this timing period, the system is shut down and the red "RESTART" lamp energized.
- E. The burner injector, which functions as a flow control valve is pulsed, causing fuel flow into the burner. A more detailed description of each event follows.

The Start switch causes relay K3 to pull in and latch through its own N.O. contacts and Q3 on board "E". A second set of K3 contacts close to provide all circuitry with power from the +28V start up battery. (Figure 33).

The fuel pump required +28VDC (supplied from start-up battery) and begins pumping. The burner injector is pulsed by a voltage controlled oscillator located on board "B" (Figure 30). The VCO is composed of Q4, Q5, XR-555, μ A798, and Section 4 of

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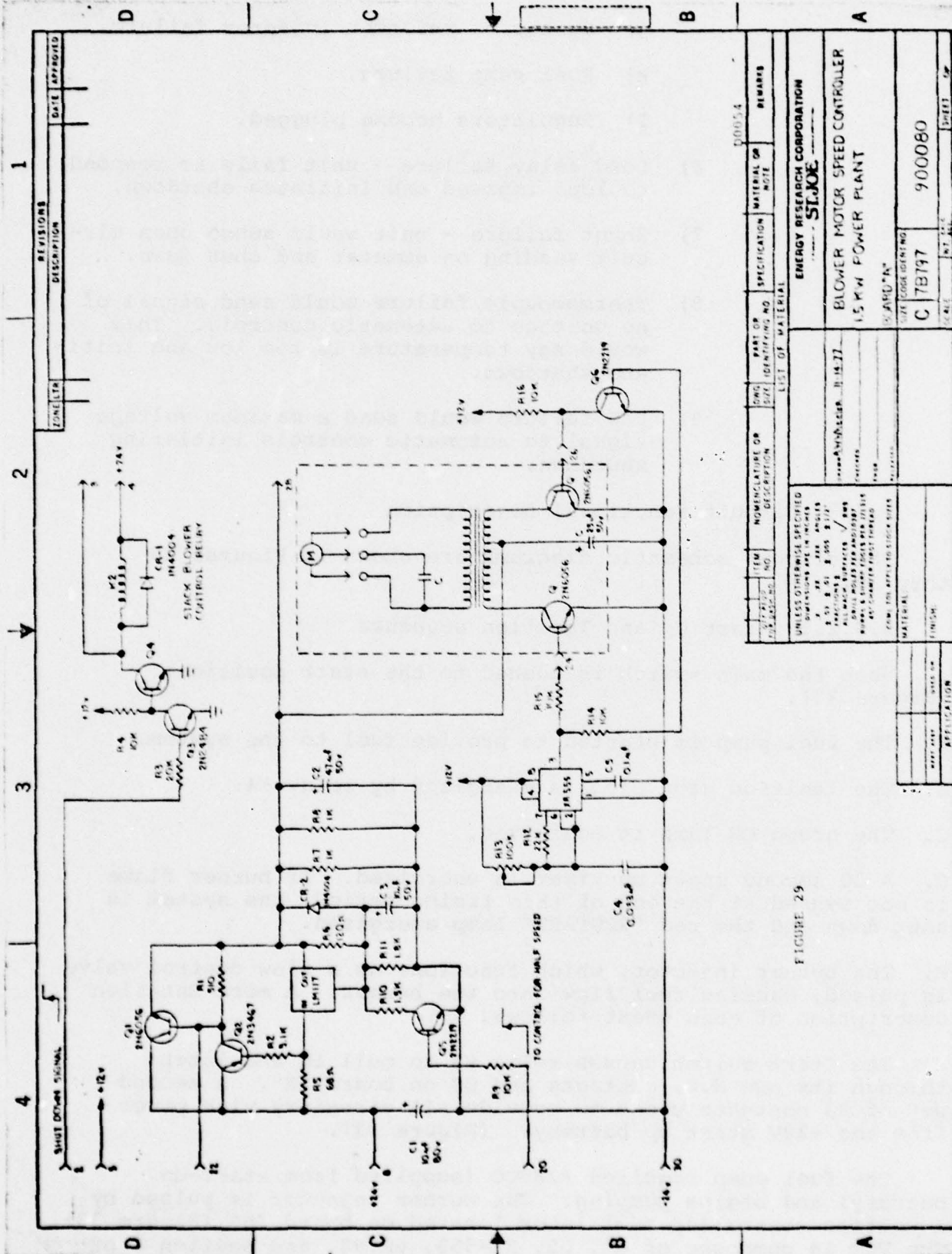
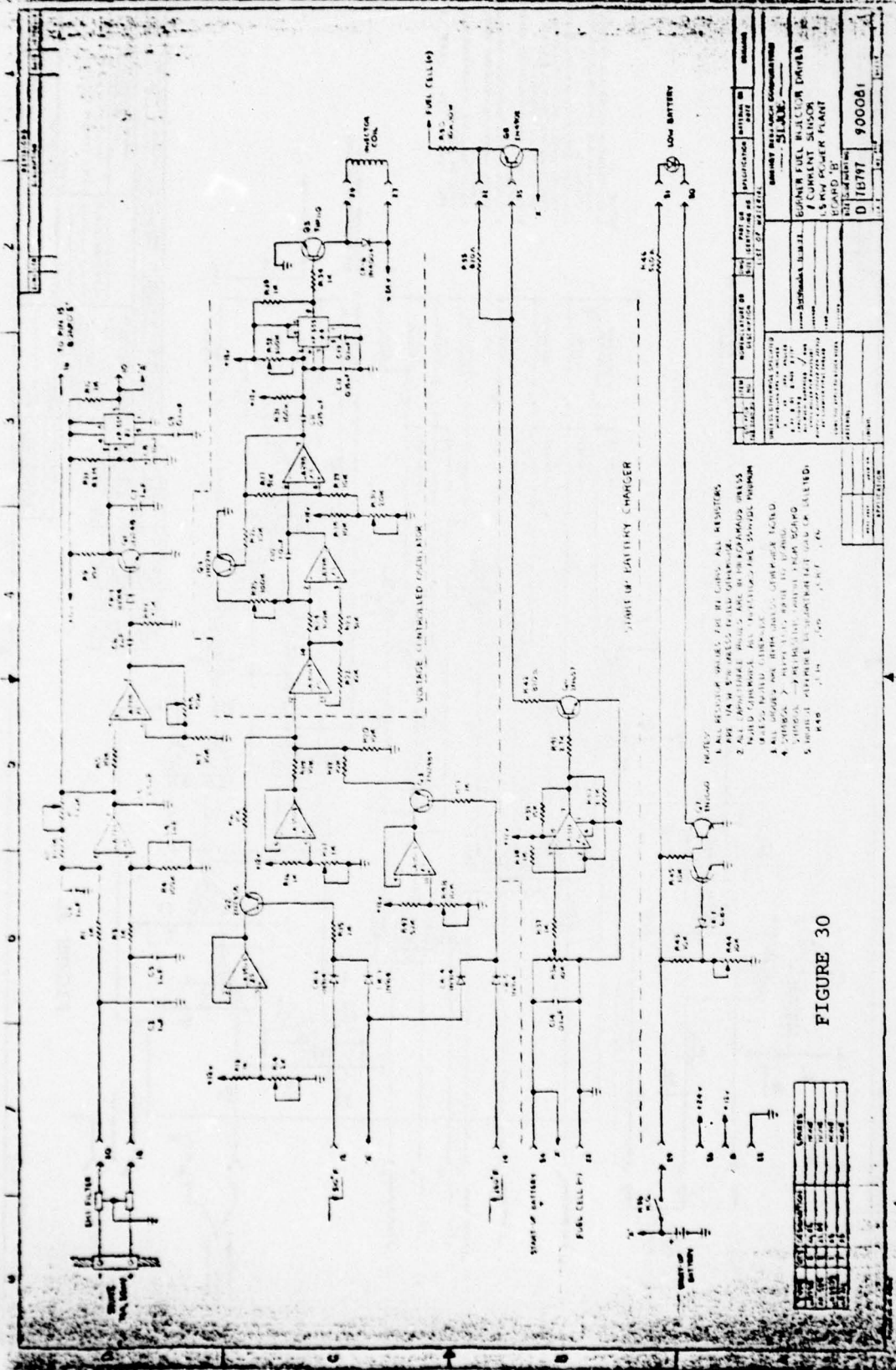


FIGURE 29

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- NOTES:
1. ALL RESISTOR VALUES ARE IN OHMS, UNLESS OTHERWISE SPECIFIED.
 2. ALL CAPACITOR VALUES ARE IN MICROFARADS, UNLESS OTHERWISE SPECIFIED.
 3. ALL DIODES ARE 1N4001, UNLESS OTHERWISE SPECIFIED.
 4. ALL OP-AMPS ARE 741C, UNLESS OTHERWISE SPECIFIED.
 5. ALL WIRING IS TO BE DONE IN ACCORDANCE WITH THE WIRING DIAGRAM.

NO.	DESCRIPTION	QUANTITY	REMARKS
1	BATTERY MONITORING	1	
2	BATTERY CHARGER	1	
3	CHARGE	1	
4	LOW BATTERY	1	
5	BATTERY MONITORING	1	
6	BATTERY CHARGER	1	
7	CHARGE	1	
8	LOW BATTERY	1	
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11	CHARGE	1	
12	LOW BATTERY	1	
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15	CHARGE	1	
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25	BATTERY MONITORING	1	
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27	CHARGE	1	
28	LOW BATTERY	1	
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40	LOW BATTERY	1	
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95	CHARGE	1	
96	LOW BATTERY	1	
97	BATTERY MONITORING	1	
98	BATTERY CHARGER	1	
99	CHARGE	1	
100	LOW BATTERY	1	

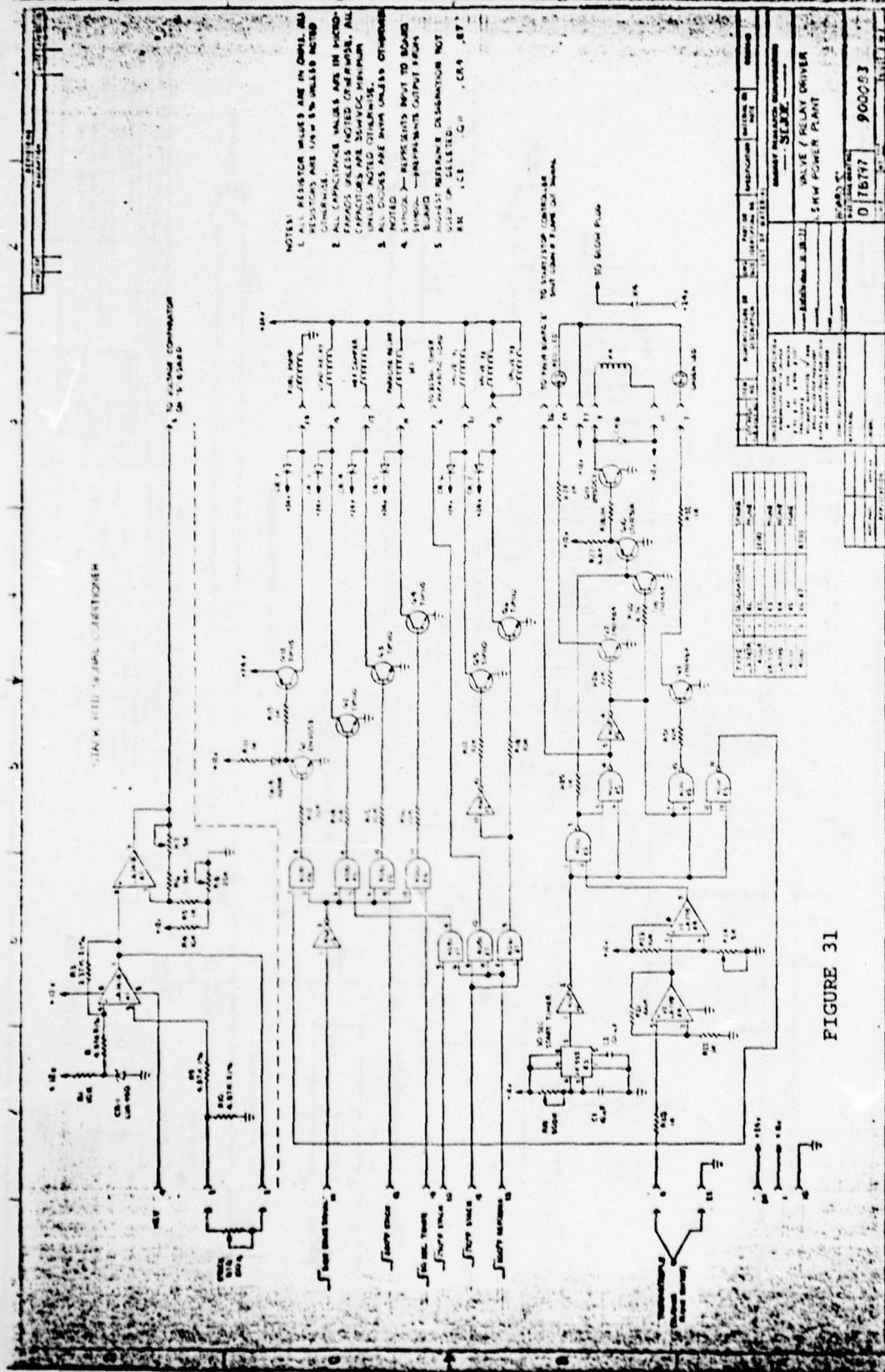


FIGURE 31

NOTES:

1. ALL PASSPORT HOLDERS ARE IN COMB. ALL REQUESTS ARE NEW TO BEATS NOTED ON CARD.
2. ALL NEW TO BEATS NOTED ON COMB. ALL REQUESTS ARE NEW TO BEATS NOTED ON CARD.
3. ALL NEW TO BEATS NOTED ON COMB. ALL REQUESTS ARE NEW TO BEATS NOTED ON CARD.
4. ALL NEW TO BEATS NOTED ON COMB. ALL REQUESTS ARE NEW TO BEATS NOTED ON CARD.
5. ALL NEW TO BEATS NOTED ON COMB. ALL REQUESTS ARE NEW TO BEATS NOTED ON CARD.

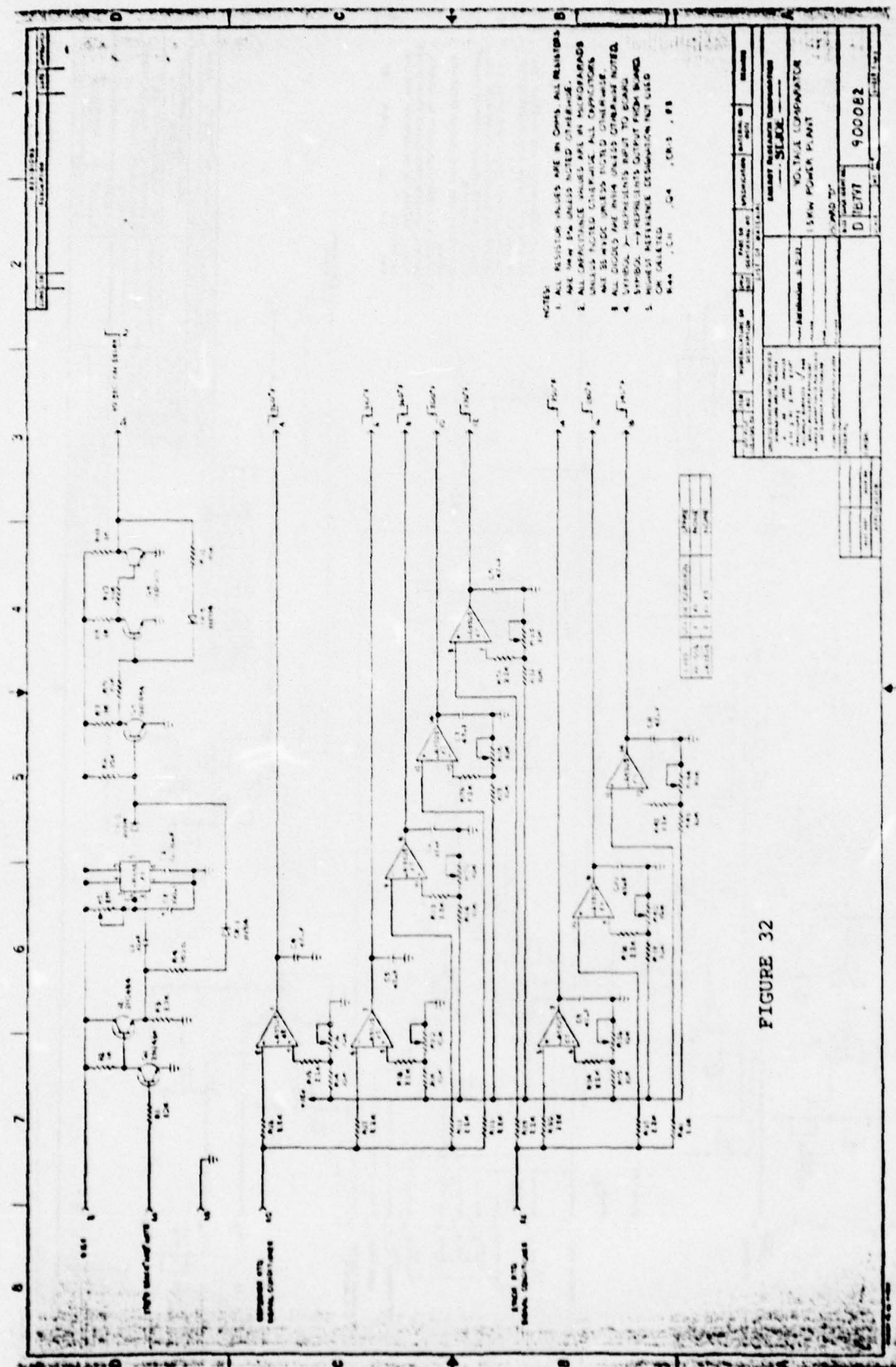


FIGURE 32

μA3503. The oscillator frequency responds to the input voltage at pin 12 of the 3503. Frequency is directly proportional to voltage where 1 volt equals 1Hz and 5 volts equals 5Hz. The injector receives a pulse of 20ms duration, whose frequency is a function of fuel flow requirements. At start-up, maximum flow is called for.

The Start switch causes relay K4 to be energized through Q11 on board "C" (Fig. 31). The green "ON" lamp is energized through Q9. The 555, 30 sec. start up timer is operated at power turn on causing pin 3 to be high, which after inversion turns off Q10 and turns on Q11. A thermocouple is provided to sense burner ignition, with the level corresponding to approximately 400°F. At the end of the 30 sec. timing period, 555 pin 3 goes low, making pin 1 of NAND gate 4011 high. If the burner has ignited, then pin 2 of the 4011 is also high, the output goes low turning Q10 on, Q11 off dropping K4 out removing power from the glow plug. Should burner ignition not be sensed, pins 5 and 6 of 4011 are both high making pin 4 low, turning on Q7 and the "RESTART" lamp. Pin 4 of the 4069 inverter goes high, which turns Q8 on, causing Q10 to go on, and Q11 off dropping K4 out. At the same time, pin 11 of the 4011 goes low, which appears at pin 1 of type 4081 AND gate. Pin 3 of the 4081 goes low, turning Q1 off which turns Q12 off, shutting off the fuel pump.

With burner ignition established, fuel flow is maintained while the reformer temperature increases. Reformer temperature sensing is performed by a Resistance Temperature Detector (RTD) installed at the reformer output. The reformer RTD is fed to a signal conditioning circuit located on board "E" (Fig. 33). A similar circuit for the fuel cell stack RTD is located on board "C" (Fig. 31). The circuit is comprised of both sections of a 747 operational amplifier arranged so that 0 to +5V equals 0 to 550°F. The conditioned RTD signal is fed to a μA3303 quad comparator located on board "D" (Fig. 32). Comparator trip points are set at 200°F, 260°F, 310°F and 360°F. A second μ3303 located on board "D" receives the conditioned stack temperature signal. The three trip points are set at 170°F, 250°F and 280°F. Each trip point will be discussed as its function takes place during this powerplant description.

At a reformer temperature of 200°F, pin 14 of the 3303 comparator goes high. This signal appears at pin 25 of board "C" (Fig. 31), and at pin 14 of board "E" (Fig. 33). No effect is produced at board "C" at this time, while Q1 on board "E" is turned on by the high signal from pin 14. The reformer voltage controlled oscillator, consisting of Q2, Q6, XR-555, and 3 sections of μA798, begins to oscillate to produce fuel flow into the reformer. Hydrogen produced by the reformer is recirculated to the burner to increase burner temperature while decreasing liquid fuel flow requirements.

At a reformer temperature of 260°F, pin 1 of the μ A3303 goes low. This signal is applied to pin 14 of board "B" (Fig. 30), which turns off Q3. Turning Q3 off reduces the voltage appearing at the summing junction of pin 12, μ A3503 section 4. The decrease is equal to the contribution made by the output of section 3 of the μ A3503 fed through Q3. Fuel conservation is further aided by reducing burner fuel flow. At a reformer temperature of 310°F, pin 7 of the μ A3303 goes low. This signal appears at pin 12 of board "B" which turns off Q2, further reducing burner flow by the contribution of section 1 of the μ A3503, reducing the level of voltage at the summing point of the VCO.

When the fuel cell stack reaches 170°F, pin 1 of the stack μ A3303 comparator goes high (Fig. 32), making pin 12 of board "C" high (Fig. 31). With the reformer above 200°F, AND gate 4081 pin 10 goes high triggering the 30 second parasitic load timer. This timer located on board "D" provides an ON delay. At the end of the delay, pin 16 of board "C" (Fig. 31) goes high making pin 11 of AND gate 4081 high, turning on Q4 which energizes parasitic relay K1. The relay disconnects the startup battery allowing the fuel cell to assume the load of the automatic control unit. The 170°F stack signal also causes AND gate 4081 pin 3 to go high, which turns on Q6 and turns off Q5. Valve V1 is de-energized, valves V2 and V3 are energized, and hydrogen produced by the reformer is allowed to enter the fuel cell stack. The fuel cell open circuit voltage comes up, and assumes the control unit load when the parasitic relay is energized.

At a temperature of 250°F, pin 7 of stack comparator μ A3303 goes high, which appears at pin 20 of board "C" (Fig. 31) causing pin 4 of two AND gates 4081 to go high, turning on Q2 and energizing the load relay. An electrical load placed across the powerplant output terminals now receives power from the fuel cell.

2.5.2.2 Operation Under Load

A. Temperature Control

At a temperature of 280°F, fuel cell stack comparator μ A3303 pin 8 goes high, making pin 18 of board "C" high, causing pin 10 of AND gate 4081 high turning on Q3, energizing the heat exchange damper solenoid. This prevents heated air from the burner from passing through the fuel cell, which is now generating heat while supplying load current. (Fig. 31).

B. Fuel flow control - Steady state condition

Flow control to the reformer is made responsive to load current and transient load increases. Fuel cell load current passes through a DC shunt rated at 50 millivolts for 75 amperes. This signal, after passing through an EMI/RFI filter appears across the input to differential amplifier μ A798 section 1A located on board "B" (Fig. 30). This amplifier is set for a gain of 100 to provide a usable signal level and keep common mode re-

jection high. The output of this stage is fed to pin 15 of board "E". (Fig. 33). The level of voltage appearing of the summing junction, pin 5 of the μ A798 board "E", is directly proportional to load current, and used to modulate the reformer injector VCO. Reformer fuel flow is thus made responsive to the magnitude of load current.

C. Fuel Flow Control - Step load change

A load increase of ten amperes is detected by a trigger circuit located on board "A" (Fig. 29). The output of the shunt amplifier is fed simultaneously to two non-inverting amplifiers, whose output is fed to a differential amplifier. The first amplifier section is allowed to follow the input immediately, while the response of the second amplifier is delayed by the 100 ohm and 100 μ f network. The differential amplifier under steady state conditions produces zero output. When a load transient occurs, pin 1 of the μ A3303 follows the input signal, while pin 7 is delayed by the R.C. time constant. The differential amplifier, set for an approximate gain of 4, goes high causing the comparator, pin 8, to go low and triggering a 555 timer. The timer acts as a 100 sec pulse generator whose purpose is to provide maximum burner flow to keep up with the increased hydrogen requirement of the fuel cell. The 555 timer signal appears at the base of Q2 and Q3 turning them on and producing maximum burner flow, and also appears at pin 16 of board "E" (Fig. 33) which increases the input to the reformer VCO, increasing reformer and burner flow are reduced to the value called for by the actual load current, as sensed by the shunt amplifier output, and fed to both burner and reformer VCO's.

2.5.2.3 Shutdown Sequence

A. Shutdown Signal

Upon pressing MAIN SWITCH to the STOP position, a set-reset latch located on board "E" (Fig. 33) is reset, and the shutdown signal at pin 20 goes high. The signal is generated from pin 3 of NAND gate 4011A which makes up one half of the flip-flop.

The shut down signal is applied to:

- a. pin 14 of board "C" (Fig. 31) where it turns off Q1 which turns off Q12 and removes power from the fuel pump.
- b. turns off Q2 which removes power from the load relay.
- c. turns off Q3 which removes power from the heat exchanger damper solenoid.
- d. turns off A4 which removes power from Parasitic relay K1.
- e. pin 2 of board "A" (Fig. 29) where it turns Q3 on and Q4 off removing power from K2 and thus the process air blower.

The flip-flop on board "E" (Fig. 33) which generated the shut down signal also triggers a XR-555 3 minute timer by turning on Q4 and turning off Q5. Pin 3 of XR-555 goes high, which holds pin 5 and NAND gate 4011B high, keeping 4011B pin 4 low, and Q7 off. C7 is held charged through R28, and Q3 is held on, keeping K3 energized. At the end of the 3 minute delay, pin 3 of the XR-555 goes low, causing pin 4 of 4011B to go high, turning on Q7. The collector of Q7 going low provides a negative going pulse to the base of Q3 turning it off, and dropping out relay K3, which removes power from the controller and the burner fan. The purpose of this delay circuit is to allow the reformer fan to continue to run, removing hydrogen which was produced during the cool down period.

2.5.2.4 Protection Circuits

The shut down circuit is activated, and the shut down signal goes high under the following conditions:

1. Reformer temperature exceeds its high limit of 500°F.
2. Fuel cell stack temperature reaches its high limit of 360°F.
3. Reformer pressure exceeds 0.95 P.S.I. due to failure of outlet valve or its driver circuitry.
4. Burner flame out, due to pump failure, exhausted fuel supply, or reformer injector failure.
5. Fuel cell voltage falling below 37 volts.

2.5.3 Operating Limitations

System electrical noise was generated by solenoid valves, relay coils, fuel pump current pulses, and the inverter-drivers for the burner and process air blower.

The present design did not prevent this stray noise from interfering with the control system basic logic. A particular problem was the current sensing circuit, which provides input to the reformer fuel flow control circuit. Improvements are required in isolation of specific circuitry and elimination of ground loops in the overall system. These problems were identified to late in the program to effectively include solutions into the deliverable powerplant. More important, however, it would now appear that microprocessor technology, not readily cost effective at the start of the project, should be used as the basis of future automatic control units. Incorporation of a microprocessor would require at least six months, using the basic powerplant logic which is assumed valid. Therefore, it was not possible to make this correction at this time.

2.6 Voltage Regulator

The voltage regulator used in the powerplant is a Gulton Industries Model EMVR 159. It supplied 1.5kW of regulated 28 V.D.C. power from the variable power input of the fuel cell. The efficiency of the regulator ranged from 86% to 92% over the power range of the unit.

The overall dimensions of the unit are 5 1/2" x 6" x 20". It weighs approximately 15 lbs. An aluminum duct was attached to the cooling fins and a Globe Industries Vane axial 15 CFM fan was employed for forced convection cooling.

2.7 Ancillary Equipment

In addition to the main subsystems, a number of ancillary components are required for the powerplant. Every effort was made in this program to utilize commercial equipment for this purpose. A list of commercially produced components and their function in the powerplant is shown in Table 8.

2.7.1 Burner

The burner assembly was purchased from the Benmar Heater Division. It is the 20,000 BTU/hr assembly. Initial attempts were made to decrease the size of the unit and increase the reliability of the dual shafted 24 V.D.C. motor. The blower and shrouding were removed and a Rotron Axi-max 2 110 volt A.C. fan motor, 40 CFM, 33 watts was secured to the back of the combustion chamber. Additional air entry holes were drilled in the chamber to allow more oxygen for combustion. During operation of the breadboard unit, local overheating of the catalyst tube banks was observed at various loads. An additional fan motor was installed in the combustion chamber. This was the Rotron Axi-max 1 23 CFM at 16 watts. It was used solely in an over-temperature situation. Further breadboard tests showed that with the 44 tube reformer the increased back pressure on the fan prevented an even heat flow through the reactor. Also, the axially mounted combustion air fan exhibited a tendency to blow out the burner flame. The air flow through the combustion chamber with the axial fan was very sensitive to back pressure in the reactor assembly. This produced cold zones in the burner and coupled with the amount of H₂O in the fuel mixture produced frequent burner flame outs. The original Benmar Burner design was re-installed in the system with some modifications. The 24 V.D.C. dual shafted fan motor was replaced with a Rotron dual shafted 28 V.A.C. 50 watts motor. The Rotron Batac Inverter was used to change the 28 V.D.C. signal to 28 V.A.C. The combustion chamber was drilled to accommodate the hydrogen inlet tube. The exterior shrouding of the burner was reduced in size and the original impellers from the Benmar fan were used supplying 40 C.F.M. The combustion air was directed radially at first in the fan assembly and then sent into the combustion chamber with increased turbulence. Subsequent testing gave favorable results. The reactor

TABLE 8

TABLE OF ANCILLARY EQUIPMENT

Component	Function	Specification	Vendor
Fuel Pump	Reformer and Burner Feed	#477883 Automotive Type 24VDC	Facet Enterprises
Flow Regulators	Pressure Regulation of Reformed Burner Feed Lines	# CA 1-5 Automotive Type	Alondra Corp.
Injectors	Meter Flow to Burner and Reformer	# V-27200-466 18-30 VDC Aircraft Type	Valcor Engineering
Burner Assembly	Combusts Liquid and Gas Feed	# C2002 20,000 BTU Assembly	Benmar Heater Div.
Blower Impellers	Supplies Combustion Air	# B2057 20,000 BTU Assembly	Benmar Heater Div.
Burner Fan Motor	Power for Combustion Air Supply	# 1834AF 28V AC Dual Shafted Motor	Rotron, Inc.
Catalytic Burner	Completes Combustion or Unburned Flue Gas Effluents	Type Torvx Platinum Coated Ceramic	Matthey Bishop, Inc.
Solenoid	Control of Heat Exchanger Damper	#174432 24VDC Tubular Solenoid	Ledex Inc.
Solenoid Valves	Direct Reformer Product Gas Flow	# V53A1020 24VDC Normally Closed 2-way valves	Skinner Inc.
Relief Valve	Pressure Relief of Reformer	# SS4CP2-1 1psi Viton Seals	Norwalk Valve & Fitting
Process Air Blower	Process and Cooling Air for the Fuel Cell	#1792 JF Propi-Max 3B 28V 400hz 70 watt	Rotron, Inc.
Bi-metallic Spring	Fuel Cell Air Recirculation Control	#1708 Operational Range 0-600°F	Crest Mfg.
Ducting	Directs Process and Flue Gas Flow	.032" and .020" Aluminum Sheet	Danbury Sheet Metal
Frame-Subframe	Envelope for Powerplant	3/4" Square Tubing Al 6061	Mohawk Aluminum, Inc.

TABLE 8 (Cont.)

Component	Function	Specification	Vendor
Shock Mounts	Dynamic Isolation of Powerplant Components	# J-8350-82 Elastomer BTRIV	Lord Kinematics
Start-Up Battery	Start-Up Power for Powerplant	# D110 10amp-hr Silver-Zinc	Energy Research Corp.
Voltage Regulator	Regulates Fuel Cell Output to 28VDC	EMVR 159	Gulton Mfg.
Fan	Cools Voltage Regulator Overload Range	19A2525 15CFM	Globe Mfg.

heat-up time was decreased from 28 minutes to 18 minutes along with a similar decrease in the frequency of burner flame outs.

2.7.2 Fuel Vaporizer

The initial design incorporated in the breadboard reactor for the 16 tube reactor was approximately 5 ft. of 1/2" wound copper tubing placed perpendicular to the axis of the reactor. See Figure 34. Initial tests yielded good results in the ability

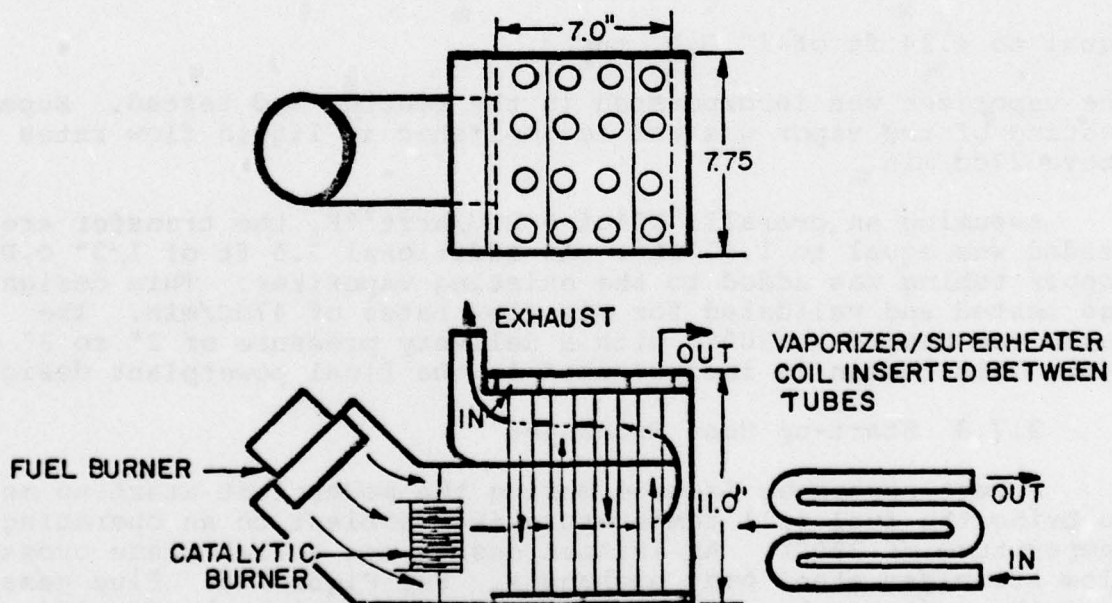


FIGURE 34 BREADBOARD REFORMER WITH VAPORIZER

of the coil to vaporize and superheat the mixture to approximately 400°F. One problem was noticed. Periodic surging of the reformer product was observed as high as 10" to 12" of H₂O. This phenomenon was due to sporadic vaporization of the liquid feed. To insure an even vaporization, copper strands were inserted into the coil. This reduced the problem significantly, i.e. the reformer outlet pressure varied only 4" to 6" of H₂O.

For the final scale up of the 44-tube reformer, a vaporizer consisting of 3 1" stainless steel tubes connected to a T-shaped superheater box was installed in the reformer. It was filled with a copper wool product to maintain good heat transfer.

The basis of vaporizer sizing was determined by the heat load needed to vaporize and superheat the liquid methanol and water feed at powerplant operation of 1.65kW net.

88ft³/hour of H₂ is the fuel cell requirement at this power level. This corresponds to 2.62 lbs/hour of CH₃OH and 1.92 lbs/hr of H₂O. The heat needed to vaporize and superheat this mixture to 300°F is 3730 BTU/hour. An assumption of an overall "U" value of 9 BTU/hrft²°F was used for the area calculation. A ΔT_{mean} of 382°F was calculated. These values substituted in

$$Q = UA\Delta T_m$$

yielded

$$A = 1.08 \text{ ft}^2$$

equal to 4.14 ft of 1" O.D. tubes.

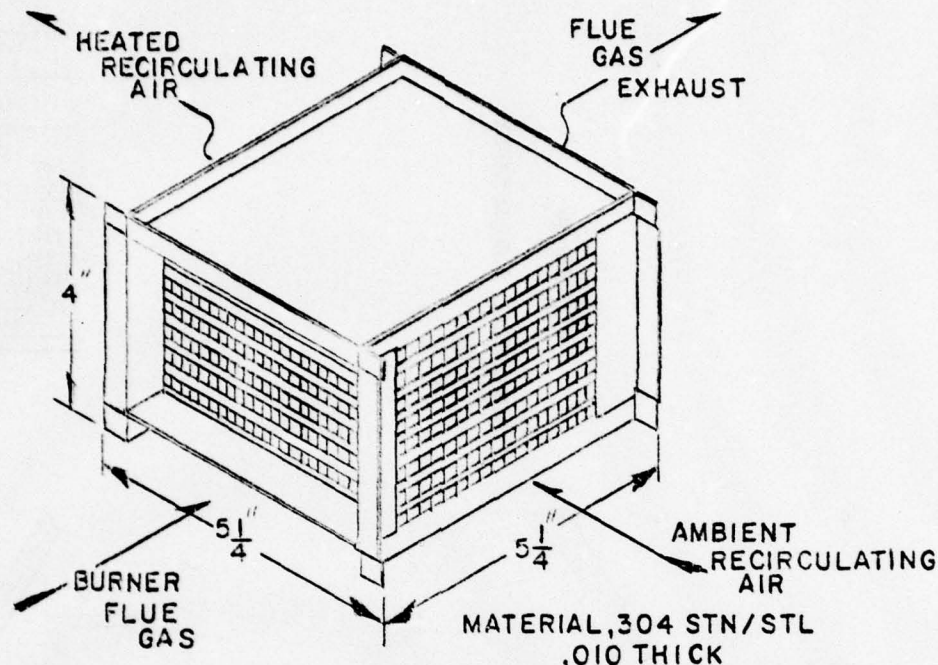
The vaporizer was incorporated in the reactor and tested. Superheating of the vapor was not accomplished at liquid flow rates above 27cc/min.

Assuming an overall "U" of 5 BTU/hrft²°F, the transfer area needed was equal to 1.97 ft². An additional 7.5 ft of 1/2" O.D. copper tubing was added to the existing vaporizer. This design was tested and validated for mix flow rates of 47cc/min. The vapor was heated to 300°F with a delivery pressure of 2" to 3" of H₂O. This design is incorporated in the final powerplant design.

2.7.3 Start-up Heat Exchanger

A heat exchanger is used during the powerplant start-up mode to bring the fuel cell temperature from ambient to an operating temperature of 250°F. An initial design was a flat plate cross flow stainless steel heat exchanger. See Figure 35. Flue gases from the reformer burner assembly are ducted through one side of the unit while recirculating air for the fuel cell passes perpendicular to this stream. The heat necessary to bring the fuel cell to an operating temperature of 250°F was calculated as 1800 BTU. A ΔT_{mean} was chosen at 190°F and a overall heat

FIGURE 35 START-UP EXCHANGER



transfer coefficient (U) was assumed at $5 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$. Heat transfer area was calculated as 1.89 ft^2 .

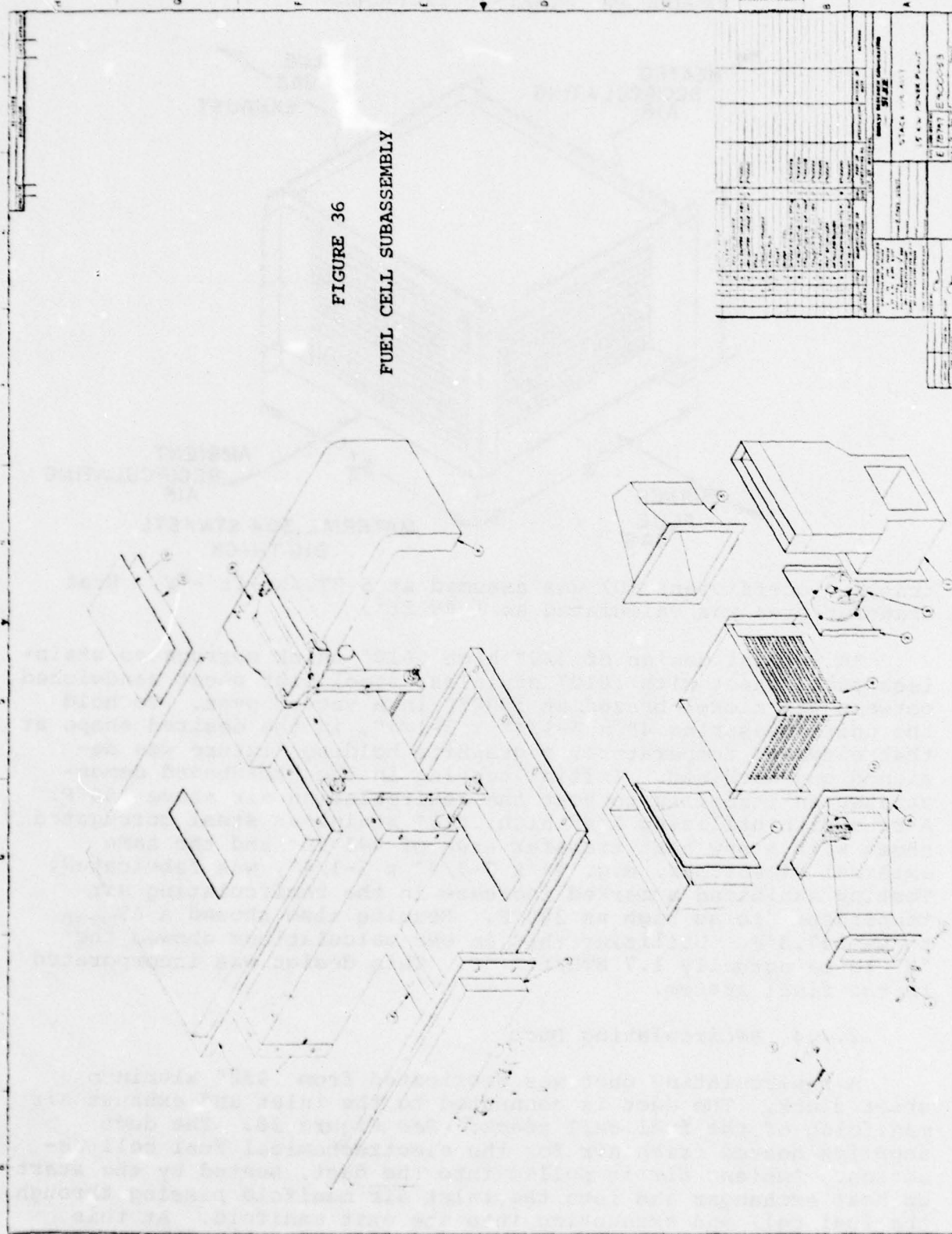
An initial design of $3/8$ " high $.010$ " thick corrugated stainless steel sheet with $.010$ " stainless steel flat sheet sandwiched between was nickel brazed at 1900°F in a vacuum oven. To hold the unit, measuring $4" \times 5\text{-}1/4" \times 5\text{-}1/4"$, in the desired shape at that elevated temperature, a graphite holding fixture was designed and machined. Initial testing in the breadboard demonstrated an inability to heat the recirculating air above 150°F . A re-design utilizing $1/4$ " high $.010$ " stainless steel corrugated sheet with a new heat transfer area of 441 in^2 and the same external dimensions, e.g. $4" \times 5\text{-}1/4" \times 5\text{-}1/4"$, was fabricated. Testing exhibited a marked increase in the recirculating air temperature to as high as 280°F . Results also showed a ΔT_{mean} to be 347.8°F . Utilizing this in our calculations showed the " U " to be actually $1.7 \text{ BTU/ft}^2 \text{ }^\circ\text{F}$. This design was incorporated in the final system.

2.7.4 Recirculating Duct

A recirculating duct was fabricated from $.032$ " aluminum sheet stock. The duct is connected to the inlet and exhaust air manifolds of the fuel cell stack. See Figure 36. The duct supplies heated fresh air for the electrochemical fuel cell reaction. Ambient air is pulled into the duct, heated by the start-up heat exchanger and into the inlet air manifold passing through the fuel cell and exhausting into the exit manifold. At this point a bi-metallic controlled damper directs the air flow into

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FIGURE 36
FUEL CELL SUBASSEMBLY



the recirculating leg of the duct or exhausts the heated air to atmosphere. During start-up, the heated air is directed into the recirculating leg of the duct to continually heat the stack to operating temperature. The fuel cell temperature rises until an air out temperature of 300°F is reached. The bi-metallic spring controlling the damper closes off the recirculating leg and simultaneously opens the exhaust leg of the duct. This passive temperature control works over the full range of stack loads. Manually operated external intake and exhaust dampers are mounted on the recirculating ducts. These are used to seal the fuel cell when the unit is not being operated.

2.7.5 Process Air Blower

The process air blower is the Rotron Propi-Max 3B 28 V.A.C. 70 watt unit. A Batac Inverter is used to invert the 28 V.D.C. power from the voltage regulator to 28 V.A.C. at 400 cps. The blower delivers approximately 130 CFM at 1" of H₂O to the fuel cell for both the electrochemical reaction and cooling of the stack plates. The unit is rigidly mounted inside the recirculating duct in front of the start-up heat exchanger.

2.7.6 Process Air Regulator

The bi-metallic coiled spring used on the recirculating damper is a Crest Mfg. P/N 1708 design operational from 0 to 600°F. The spring is incorporated in a damper assembly located directly above the air exhaust from the fuel cell. The coil is pre-stressed to begin damper actuation at an air temperature of 300°F. Damper movement continually changes the volume ratio between recirculated and exhaust air. At a temperature of 340°F, the damper is in full open position exhausting all air from the stack. Since the recirculating duct is an open loop in this mode, a maximum of ambient air is allowed into the stack for cooling.

2.7.7 Start-up HEX Solenoid

The start-up heat exchanger damper is controlled through a mechanical linkage by a Ledex Inc. 10 watt solenoid. At start-up of the powerplant, the damper is in an open position, solenoid de-energized, allowing reformer burner flue gases to pass through a duct to the start-up heat exchanger. There the heat is transferred to the process air stream and utilized for fuel cell warm-up. When the fuel cell is at operating temperature as indicated by a thermocouple in stack air exhaust, the solenoid is energized, closing the damper and directing all flue gases through the reformer.

2.7.8 Solenoid Valves

Three Skinner Inc. 3/8" orifice 28 V.D.C. solenoid valves rated at 10 watts are used to direct reformer product gases through the powerplant. The internal seats of the valves are made of Viton to withstand the elevated reformer gas temperatures of

approximately 300°F. During initial hydrogen production by the reformer, valve 1 (V1) directs the gas flow to the burner. When the fuel cell is raised to an operating temperature, V1 closes and V2 and V3 open directing hydrogen to the fuel cell. The valves are a normally closed type. These were chosen to protect the reformer catalyst from oxidation in case of power failure during system operation.

2.7.9 Catalytic Burner

Two catalytic burners are employed in the powerplant. They are Mathey-Bishop Inc. Torvx Type 1 ASTM Mesh Size 12 with Platinum deposited on a ceramic honeycomb catalytic burner. Both are placed downstream of the burner assembly to complete combustion of hydrogen or unburned products of the liquid burner fuel. One is placed between the burner assembly and the catalyst tubes, the other in the start-up heat exchanger duct so that all combustion flue gases are reacted before exiting the powerplant.

2.7.10 Fuel Pump

A single fuel pump is used to pressurize fuel to the burner and reformer. It is a Facet Enterprises 24 V.D.C. automotive type pump. Pump power consumption is 9 watts at a delivery pressure of 4 1/2 psi.

2.7.11 Pressure Regulator

Two Alondra Corporation adjustable automotive type pressure regulators are utilized in the burner and reformer feed lines. These are used to maintain a constant downstream line pressure to the injector valves.

2.7.12 Injectors

The reformer and burner injector valves are Valcor Eng. Corp. 2-way normally closed 18-30 V.D.C. solenoid valves. The valves are pulsed in an on/off mode to meter flow accurately to the burner and reformer. Both injectors receive signals from the automatic control unit. The burner injector rate is controlled by the reformer exhaust temperature. As this temperature increases, flow is reduced to the burner. The reformer injector is responsive to the amount of external load applied to the powerplant. An increase in load amperage increases the reformer injector metering rate by a corresponding amount.

2.7.13 Pressure Relief Valve

A Circle Seal Inc. pressure relief valve is located immediately downstream of the reformer. It is set to open at 1.1 psi. It is designed to pass 4.85 CFM of air at 70°F. The seals in the valve are all Viton to withstand the 300°F reformer gases. The valve maintains system pressure within safe limits so as not to damage other system components such as seals in the fuel cell stack.

In conjunction with the relief valve, a Consolidated Controls Corporation high temperature pressure switch set at 0.95 psi is utilized in the event of a component failure such as the 3 solenoid valves V1, V2, or V3. The switch signals the Automatic Control Unit to initiate a unit shutdown if set pressure is exceeded.

2.7.14 Battery

A start-up battery for the powerplant consisted of 17 10 amp-hr silver-zinc cells yielding 25.5 volts. The 17 cells were placed in a stainless steel box measuring 15 3/8" x 15 3/8" x 7/8" and attached to the powerplant frame. A Vernay Laboratories umbrella type relief valve was included in the box to vent pressurized gases during battery re-charging.

The fuel cell provides power to recharge the startup battery as soon as it accepts parasitic load. The charger used provides a charging current of about 1.0A, recharging the battery in under 4 hours after startup. As the battery accepts charge and its terminal voltage comes up, the potential difference between battery and charger is reduced, and the charging current is reduced. A trickle current of 0.100 ampere is maintained to keep the battery fully charged.

The charger is located on board "B" and shown in zone B-5 of drawing 900081. A Low Battery lamp is provided to indicate there is insufficient battery capacity to bring the powerplant up from a cold start.

3.0 BREADBOARD POWERPLANT TESTING

The breadboard testing was needed to achieve confirmation of component design and performance as part of a system. The interdependence of subsystems was obtained. This led into the transfer of operation control to the electronic control circuitry.

The first breadboard unit consisted of a 16-tube reformer (catalyst volume 215in³), an 80-cell stack, basic automatic control circuitry, a voltage regulator, and an electrical load bank and meter panel. See Figure 37. The load bank consisted of a carbon pile load for direct conversion of generated power to heat and testing of the fuel cell and an automotive sealed beam headlamp load bank for testing the system with the voltage regulator.

Initial testing was conducted to verify the design validity of the various components, e.g. heat exchanger, control circuitry, reformer, the 80-cell stack, damper designs, burner assembly, blowers, etc., and the physical arrangements of the unit. Also,

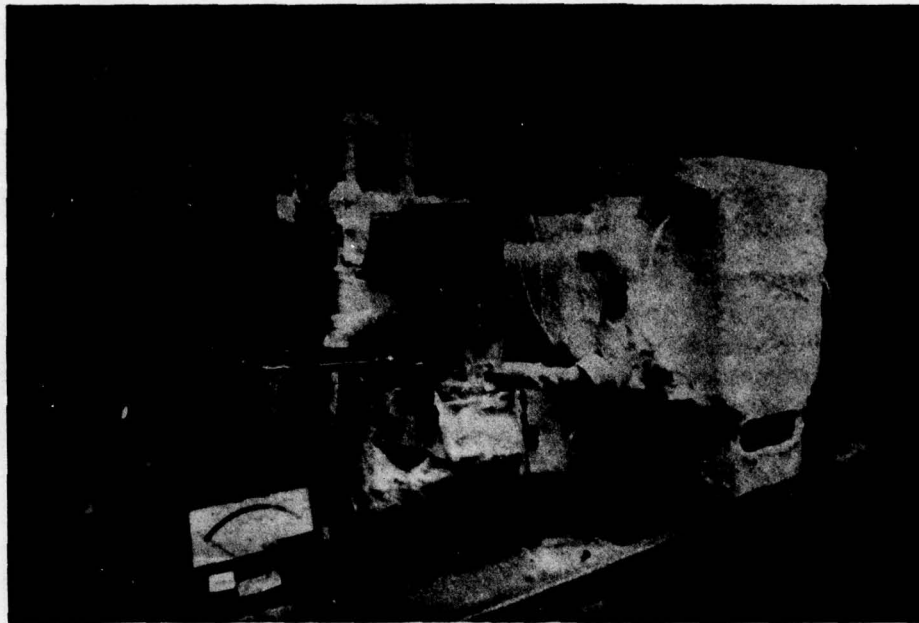


FIGURE 37 Breadboard Powerplant

testing was aimed at establishment of a control logic for fully automatic operation of the unit.

Initial testing of the powerplant yielded an output of 1512 watts gross power from the fuel cell. This corresponds to 75% net power of the full rated load. System problems were identified at this time.

First, the recirculating air damper system was found to restrict the fresh air intake for stack cooling. Accordingly, damper placement and actuators were re-evaluated. One damper was eliminated and the second was placed in the fuel cell air outlet stream. In this position the damper could simultaneously control the volume of fresh air and the volume of recirculating air.

The original fluid bulb, capillary tubing, and bellows damper actuator setup for stack temperature control was found to be bulky and unreliable over the operating temperature range. This system was replaced with a bi-metallic spring as the damper actuator. The spring is exposed to stack air exhaust and operates reliably over the temperature range of the stack.

The start-up heat exchanger had 3/8" high corrugations and was placed in an 18" long duct connecting to the combustion chamber. Results showed the air flowing to the stack could not be heated above 150°F with this arrangement. Ducting to the heat exchanger was considered too long, and the heat exchanger itself had too little heat transfer area. The heat exchanger

was redesigned with 1/4" high corrugated stainless steel sheets, which produced an increase of 60% in the heat transfer area. Also, the hot flue gas diverter duct was shortened. To accomplish this, the recirculating duct was turned 90° to the vertical axis of the fuel cell. Instead of the ducting going over the tie-rods of the stack, it was placed between the rods. This arrangement allowed air into the stack to be heated to approximately 280°F. It also reduced the volume of the fuel cell subsystem from 1.85ft³ to 1.75ft³.

Preliminary unit response tests were conducted. The reformer with a catalyst volume of 215in³ was found to be insufficient in capacity to handle up-load changes. Response time to load increases was considered excessive with a unit steady state established after 2 to 3 minutes. A new reformer was designed as described in Section 2 with a volume of 450in³. It consisted of 44 1" diameter tubes arranged in a staggered sequence to help heat transfer to the catalyst.

The change in the reformer geometry adversely affected the burner assembly. The staggered reformer tubes caused an excessive pressure drop for the burner axial flow blowers, ascertained by uneven temperature distribution in the reactor bed. They were replaced by the original Benmar Burner assembly utilizing a dual shafted motor with two centrifugal impellers. Heat flow was conducted evenly through the reactor assembly and the methanol-water mixture was observed to combust with less frequency of the flame outs than previously noticed.

The basic control logic was defined by operation of the breadboard. Start-up, shutdown sequences, unit response to out of range parameters, and steady state operation were accomplished with the automatic control unit. See Section 2.5 for Control Logic.

With the integrity of all components assured and redesign accomplished, a series of tests were conducted to determine unit characteristics.

The first test conducted was for start-up and hot idle. Conditions were established to enable the unit to hot idle, i.e. maintaining reaction temperatures in the reformer and the stack and having the unit produce enough power to run the parasitic equipment load. The parasitic load was 4A at 57 volts = 228 watts. The fuel consumption for the unit averaged for 4 hours was 1.17 lbs/hr of methanol. This represented 10cc/min to the burner and 8cc/min to the reformer.

Fuel cell stack hydrogen utilization tests were carried out to verify calculations as to the amount of excess hydrogen needed to maintain the endothermic reforming catalyst at a reaction temperature over the load range of the powerplant. Results indicated the stack utilization should be in the 65% to 70% range. The utilization was increased to 75% in the final system by

increasing the amount of insulation on the reformer subassembly from 1/8" to 1/4" thickness.

The next series of breadboard tests were directed at determination of unit start-up time. Fuel was fed to the burner at a rate of 23cc/min. The reformer catalyst reached a reaction temperature in approximately 20 minutes. The fuel cell stack heat up rate lagged the reformer. It reached 160°F, which is hot enough for the cell to assume the parasitic load, within 27 minutes. The cell temperature increased to 250°F in 40 minutes from start whereupon an external load was able to be supported.

Further tests were conducted on load response of the unit. The breadboard unit was started and brought to a "hot idle" condition. This idle rate was maintained for 1 hour at 5 amp and 56 volts with both fuel cell and reactor at optimum operating temperatures e.g., catalyst bed at 400°F and fuel cell plate temperature at 320°F.

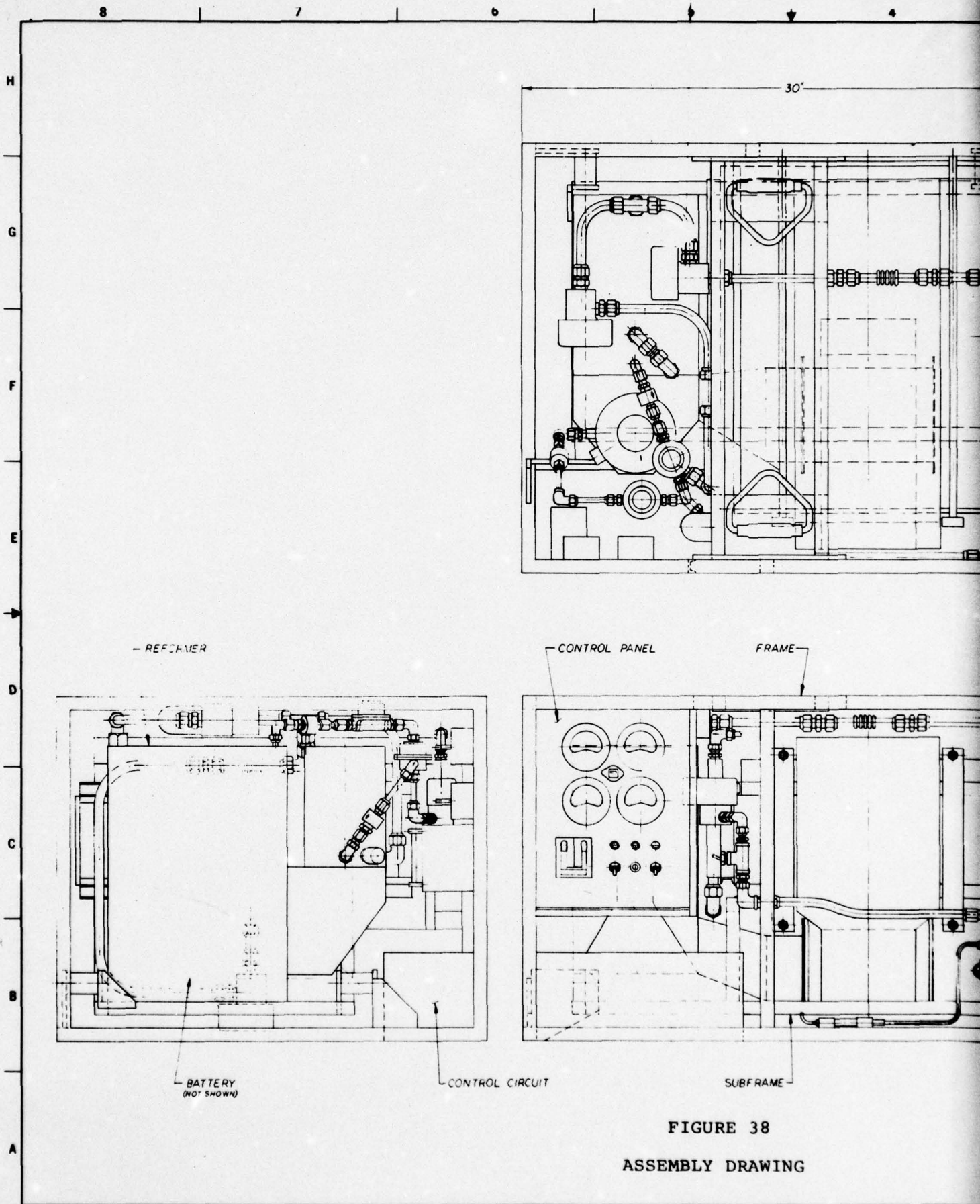
The initial tests were run by manually applying load and increasing reformer feed correspondingly. The maximum load step, which was successfully accomplished by the unit, was an increase from 5 amps and 56 volts to 30 amps at 46 volts which represents a 1.1kW increase. This load was supported for one hour with an average fuel feed rate to the reactor and burner of 26ml/min and 10ml/min, respectively. This represents a methanol feed rate of 2.35 lbs/hr.

Further breadboard testing was directed at full automatic unit operation. Start-up and shutdown controls were installed and tested satisfactorily. Their operation is described in the section on the Automatic Control Unit. The controls for steady state operation and load response were added to the breadboard. Steady state operation was accomplished. Problems developed with the ability of the unit to accomplish up-load response changes. The control circuitry was believed to be affected by electrical noise generated by the other components in the powerplant. Isolation was not accomplished. This control problem is discussed in the Automatic Control Unit Section.

4.0 POWERPLANT CONSTRUCTION

Based on information gathered in breadboard testing, the Model A powerplant construction began. See Figure 38, Assembly Drawing.

A frame of 6061T6 Aluminum 3/4" square tubing, 1/8" wall thickness, was welded together with outside dimensions of 29 1/2" x 24" and 18 1/2". This means a volume of 7.6 ft³ for the powerplant. Gussets were welded at corner junctions to increase main frame rigidity. A subframe was assembled and shock mounted to the main frame utilizing Lord Kinematics, Inc. hard rubber mounts. The mounts were installed in a shear plane. The subframe supported the weight of the reformer and the fuel cell



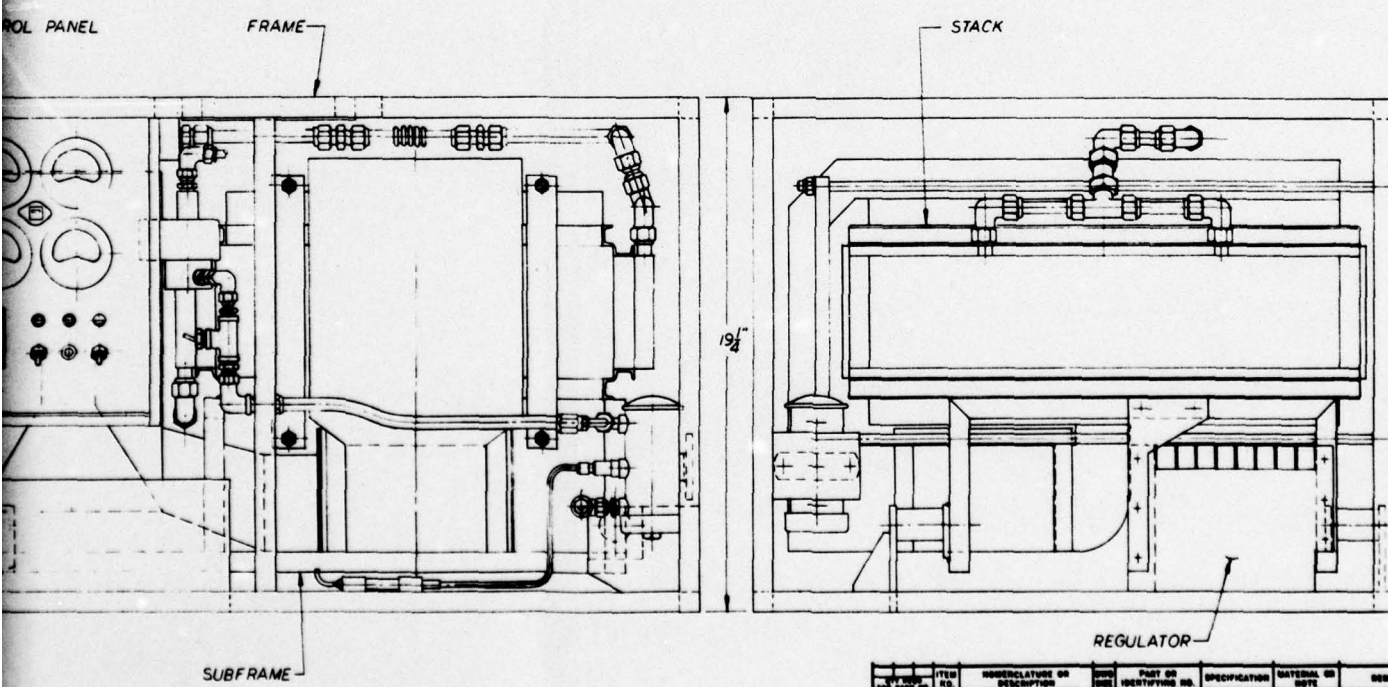
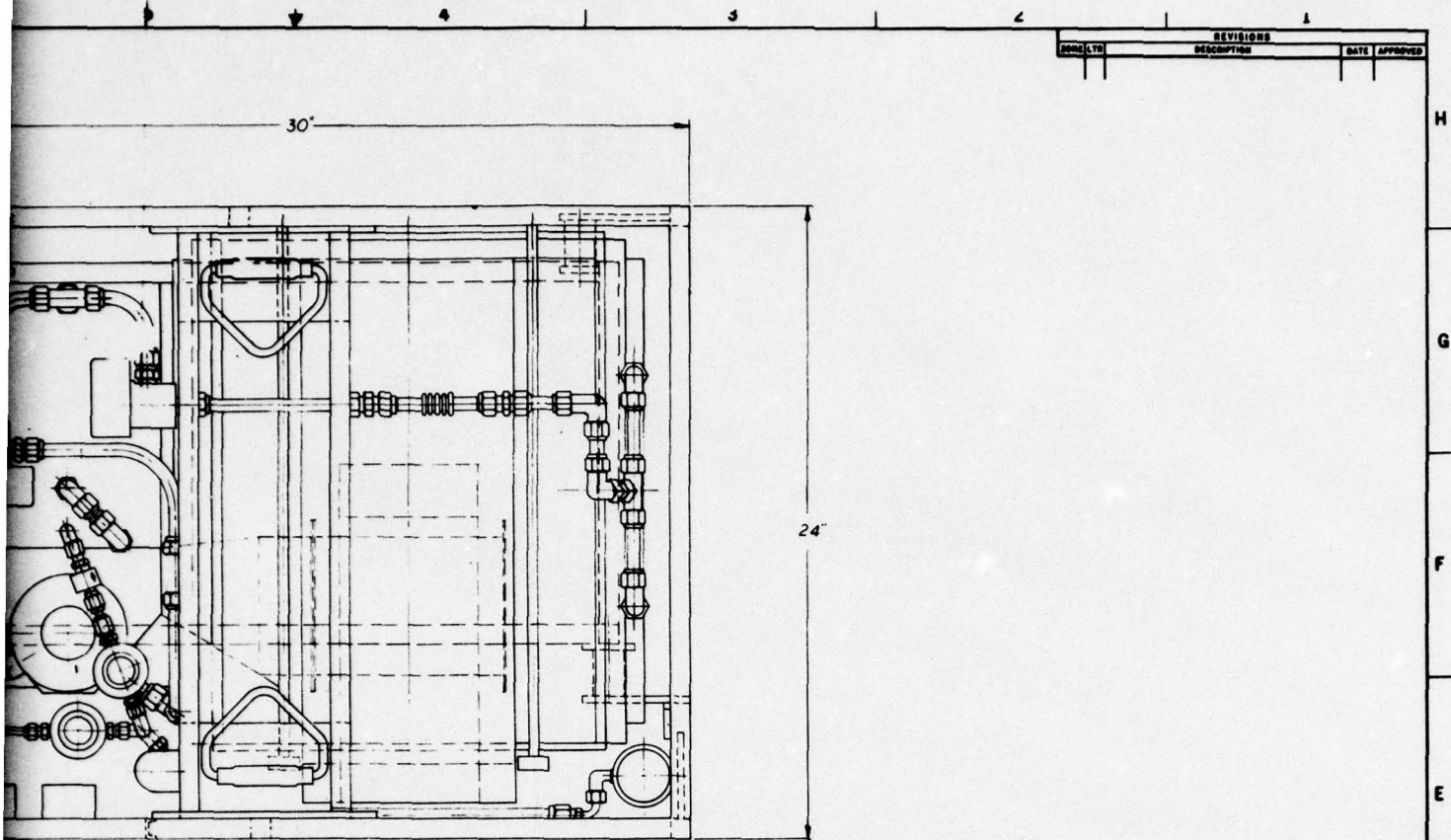


FIGURE 38
ASSEMBLY DRAWING

ITEM NO.	DESCRIPTION	QTY	PART OR IDENTIFYING NO.	SPECIFICATION	MATERIAL OR NOTE	REMARKS
LIST OF MATERIAL						
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES FRACTIONS < 1/8" USE DECIMALS ALL DIMENSIONS SURFACES DRILL HOLES PER AMERICAN BUREAU OF STANDARDS PER ANSI 1ST CLASS FIRST TUBES CUT TO LENGTH TO STOCK SIZES						
MATERIAL:				15 KW POWER PLANT		
NEXT ASST. USED IN:				E 000054		
APPLICATION:				E 000054		

subsystem. The main and subframes including the lifting attachment with assorted hardware weighed 13.5 lbs.

The recirculating duct, heat exchanger, and flue gas intake and exhaust ducts were attached to the fuel cell manifolds and placed on the subframe. See Figure 36, Stack Subassembly. The reformer subsystem was next installed. Six 8-32 bolts secured the combustion chamber of the reformer to the heat exchanger intake duct. Brackets mounted the reformer to the subframe. See Reformer Subassembly, Figure 39.

The control panel with 2 ammeters, 2 voltmeters, a circuit breaker, 2 on/off toggle switches, and 3 status lights was installed on the main frame with two quarter-turn fasteners.

Next, the Gulton Industries voltage regulator with a small cooling fan and attached duct was installed under the fuel cell.

The plumbing of liquid and gas lines to the reformer and the fuel cell stack were routed through the unit, tightened and then leak tested.

The start-up silver-zinc battery was charged and installed in the frame envelope.

The wiring of all electrical components into harness bundle was completed, and then the automatic control unit was installed.

All hot components, e.g. reformer subsystem and fuel cell subsystem, were incased with a WRP-X-AQ "felt wet pak" 1.4" thick. An additional layer of aluminized fiber insulation was added and all components were painted olive drab. Figure 40 shows a photograph of the powerplant.

5.0 POWERPLANT TESTING

The completed 1.5kW Powerplant weighed 258 lbs. and occupied a volume of 7.6 ft³. A complete weight breakdown is included in Table 9. The powerplant was set up for testing as described in the Quality Assurance of the Purchase Description.

Voltmeters, ammeters, thermocouples, a graduated cylinder, and 2 rotameters were installed in the test set-up to determine unit operating parameters, e.g. stack voltages, stack amperes, temperature profiles of components and fuel consumption at different external load levels.

During the testing of the powerplant, automatic start-up was achieved to the idle condition. From the point to full load conditions, it was necessary to make manual adjustments to operate

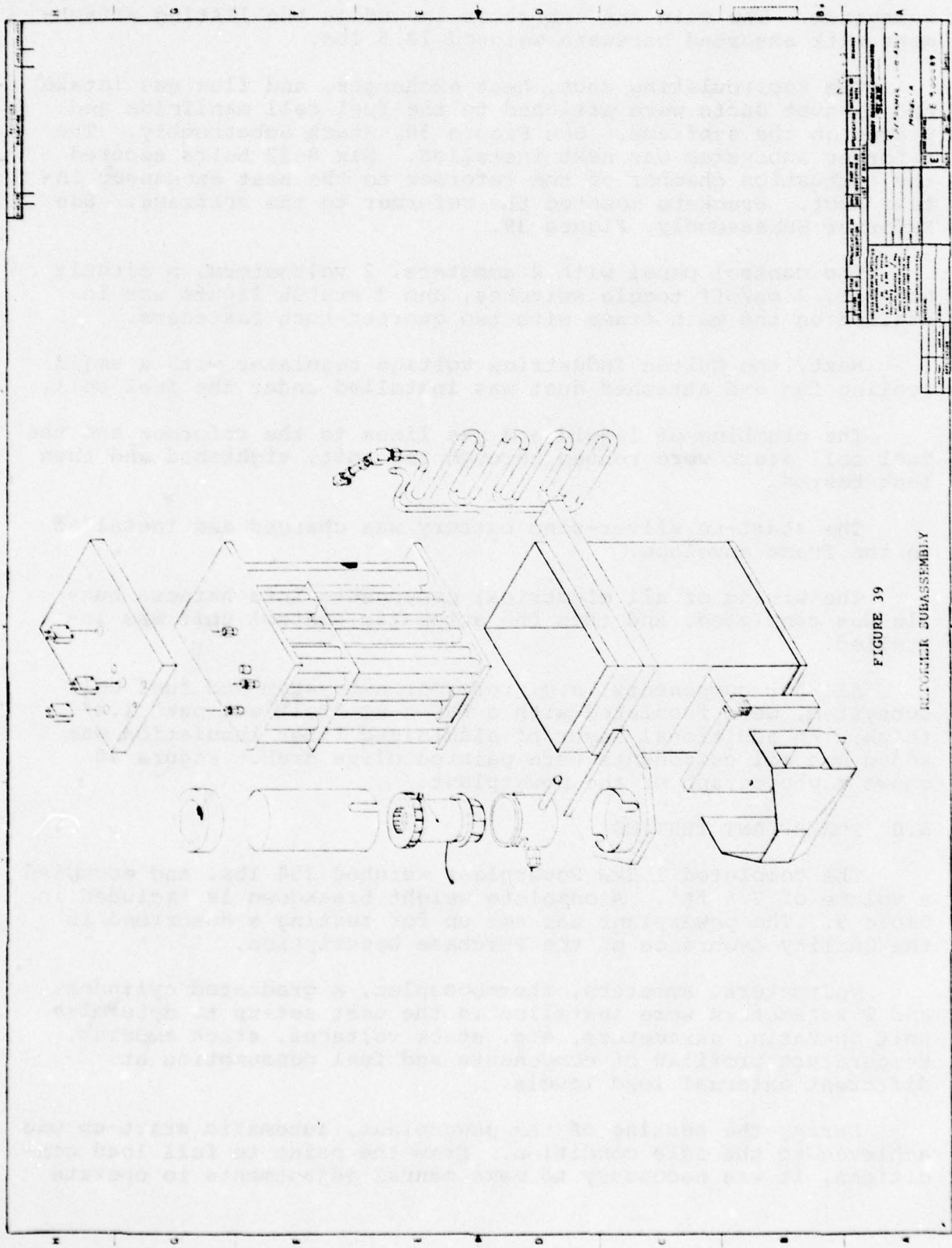


FIGURE 39
FUELER SUBASSEMBLY

REVISIONS		DATE		BY	
1	INITIALS	2	DATE	3	BY
APPROVED FOR RELEASE		DATE		BY	
REVISIONS		DATE		BY	
1	INITIALS	2	DATE	3	BY
APPROVED FOR RELEASE		DATE		BY	

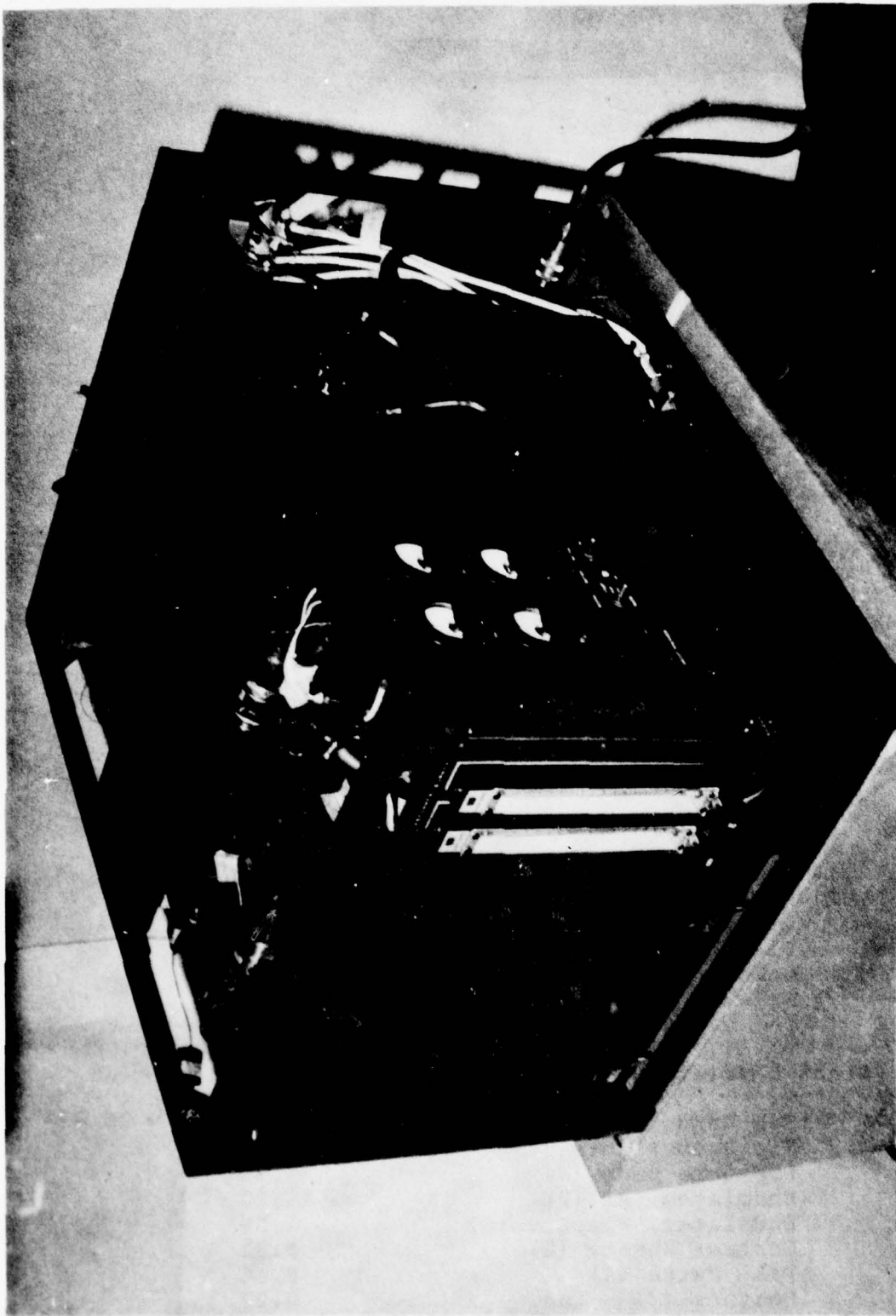


FIGURE 40 1.5 KW METHANOL FUEL CELL POWERPLANT

TABLE 9

POWERPLANT WEIGHT

Fuel Cell	
Stack	49.35
Stack Hardware	28.38
Manifolds	28.42
Total Fuel Cell	106.15
Reformer	55.0
Voltage Regulator	15.0
Frame & Mounts	13.50
Miscellaneous	68.65
Total Powerplant	258.30 lbs.

COMPONENT WEIGHT

<u>Component</u>	<u>Weight, lbs</u>
Fuel Cell	
80 cells	
Bipolars (81)	38.31
Electrodes (160)	3.34
Matrices (80)	1.41
Ta strips (160)	0.70
Electrolyte (15 ml/cell)	4.75
Cement (5g/cell)	.84
Subtotal	49.35
Stack Hardware	
Tie Bars (2)	7.92
Tie Rods & Nuts (4)	2.11
Pressure pads (8)	.79
Endplates, Al (2)	14.78
Endplates, Plastic (2)	1.54
Contact Sheets (2)	0.31
Fill Parts (4)	0.66
Heaters (2)	0.27
Subtotal	28.38

TABLE 9

(Cont.)

Manifolds

Air Manifolds (2)	10.00
Fuel Manifolds (2)	5.00
Manifold bolts	0.92
Hex with blower	10.00
Hex duct	2.50
	<hr/>
Subtotal	28.42
	<hr/>
Total	106.15

Reformer

Reactor

Tubes (44)	11
Plenums (2)	1.5
Vaporizer	2.4
Reforming Catalyst	22.0
	<hr/>
Subtotal	36.9
	<hr/>
Reformer Shell	3.20
Reformer Shell Top	1.0
Catalytic Burner	1.0
Combustion Chamber	1.5
Burner Assembly	2.1
Blower Motor	2.75
Burner Shroud	1.25
Exhaust Duct	.85
Thermocouples	.45
Welds	.50
Insulation	3.50
	<hr/>
Subtotal	18.10
	<hr/>
Total	55.0

TABLE 9

(Cont.)

Miscellaneous

Start-up Battery	16.0
Control Panel	4.3
Solenoid Valves (3)	5.3
Injectors (2)	0.4
Fuel Pump	1.7
Load Relay	1.3
Controller	10.0
Blower Transformers (2)	3.0
Pressure Regulators (2)	.8
Solenoid Damper Control	1.0
Insulation	7.0
Power Wire	2.75
Pressure Switch	1.0
Plumbing	9.0
Misc. Electrical Wire	1.0
Misc, Nuts and Bolts	3.9
Subtotal	68.65 lbs

the unit as spurious noise signals interfered with the current sensing shunt signal for automatic fuel flow control. While it is necessary to correct this deficiency, described in detail in the ACU portion of the report, ERC believes that these electronic problems are minimal and can be readily corrected in future programs.

The unit was started with fuel consumption and time to idle conditions determined. The burner start-up rate was measured at 1.58 lbs/hr of CH_3OH . The time to reach idle conditions - e.g. reformer catalyst at an average temperature of 400°F and the fuel cell at a temperature of 250°F with the fuel cell energizing all parasitic components, was 40 minutes. The parasitic load was measured at 210.7 watts. See Table 10. The fuel consumption at idle was measured at 1.1 lbs hr of CH_3OH .

External loads were applied to the powerplant at small percentage load increments. A gross power level of 672 watts was the initial step. The net power was 370.5 watts corresponding to approximately 25% load. The unit was allowed to reach steady state conditions and the fuel consumption was measured at 22cc/min of total mixture. This represents 1.5 lbs/hr of CH_3OH .

The power increment was then increased to approximately 50% load. The gross power level was measured at 1035 watts. The net power was 741 watts. The unit was operated at this power level until temperatures stabilized. The fuel consumption was measured

TABLE 10

Parasitic Load Requirements

Component	Power Consumed (watts)
Glow Plug (at start-up for 30 secs.)	240.0
Fuel Pump	8.4
Burner Injector	5.6
Reformer Injector	5.6
Solenoid Valves (V1 and V2)	20.0
Heat Exchanger Damper Solenoid	13.7
Voltage Regulator Cooling Fan	12.0
Parasitic Load Relay	6.0
Load Relay	17.4
Burner Blower	49.5
Process Air Blower	72.5
Total	450.7 watts at start-up
	210.7 watts at steady state

at 27cc/min of mixture representing 1.85 lbs/hr of CH_3OH .

The unit power level was increased to 1419 gross watts and a net of 1083 watts. This corresponds to 75% load. Again the unit was allowed to stabilize and fuel consumption was measured at 36cc/min total equaling 2.47 lbs/hr of CH_3OH .

The powerplant was brought up to nominal power at 40 volts and 46 amps equal to 1840 watts. The net power was equal to 1454 watts.

The specific fuel consumption was measured at 44cc/min of mix or 3.1 lbs/hour of CH_3OH .

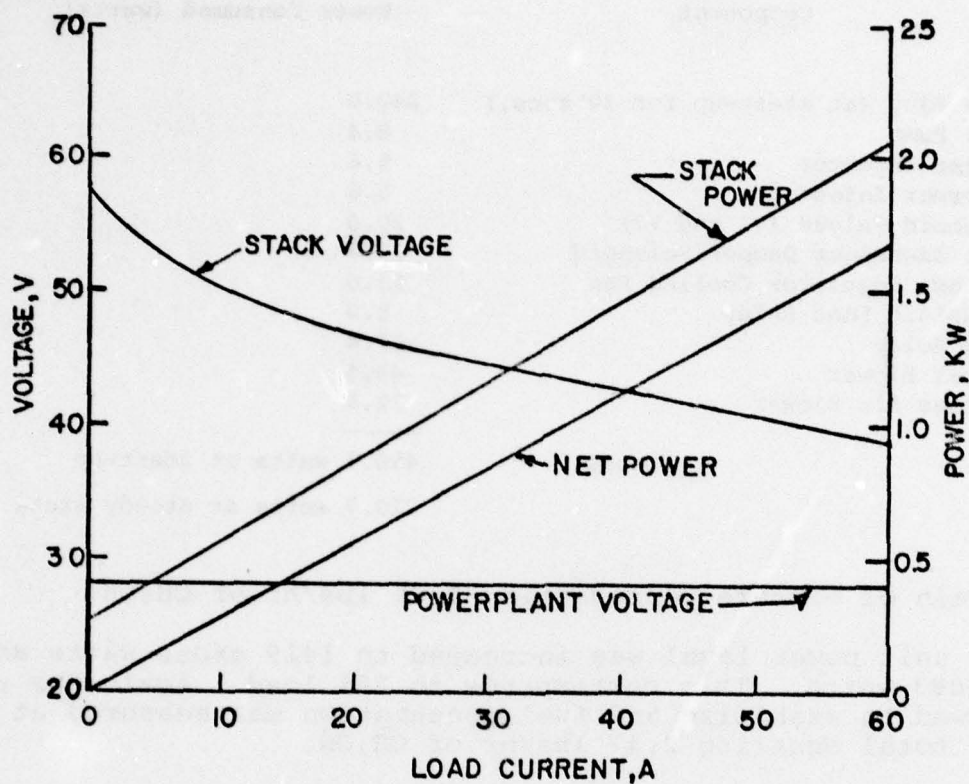
The final increase in load demonstrated the units ability to accomplish the 110% load demand. The gross power was equal to 2.028kW with a net power equal to 1.65kW. After temperature stabilized, the total fuel consumption was measured at 48cc/min or 3.3 lbs/hr of CH_3OH .

Powerplant and stack performance are plotted in Figure 41.

Gross and net efficiencies for the powerplant were calculated and included in Table 11. The value of 328,700 BTU/lb mole of the CH_3OH was utilized in the calculations.

The powerplant was shutdown, final packaging and cosmetic work was completed, and then the unit was delivered to MERADCOM.

FIGURE 41 Powerplant Performance



D0064

TABLE 11

POWERPLANT TEST RESULTS

Net Regulated Power (Watts)	Net Load Amperage (Amps)	Net Load Voltage (Volts)	Unregulated Net Power (Watts)	Parasitic Power (Watts)	Stack Power (Watts)	Stack Current (Amps)	Stack Voltage (Volts)	Fuel Consumption lbs/hr CH ₃ OH	Gross Efficiency %	Net Efficiency %
—	—	—	—	210.7	228	4	57	1.10	6.9	—
370.5	13.0	28.5	598.5	210.7	672	14	48	1.50	14.9	8.2
741.0	26.0	28.5	969.0	210.7	1035	23	45	1.85	18.6	13.3
1093.0	39.0	28.5	1311.0	210.7	1419	33	43	2.47	19.1	14.6
1458.0	51.0	28.5	1682	210.7	1840	46	40	3.1	19.7	15.6
1853.0	58	28.5	1881	210.7	2028	52	39	3.3	20.4	16.6

6.0 WATER RECOVERY STUDY

The 1.5kW indirect methanol-air fuel cell powerplant requires 1.3 moles of water per mole of methanol in the reformer feed. The two powerplant effluent streams - burner flue gas and process air from the fuel cell stack - contain water vapor. If a method for the recovery of this water can be devised, it could be combined with the feed methanol, doing away with the need to supply external water to mix with feed methanol.

The amount and concentration of water vapor in the effluent streams depend upon the operating conditions and the ambient conditions. The powerplant heat losses to the surroundings vary with ambient temperature, which affect the amount and concentration of water vapor in the effluent streams. If the water vapor recoverable from the effluent streams is sufficient for the feed, it can be recycled and the need of supplying external water can be eliminated. This study investigates the feasibility of water reclaim.

6.1 Development of Water Availability Matrix

An assessment of total water available in the effluent streams and the feed water requirements at various operating and ambient conditions was carried out. The conditions studied are listed below.

Load conditions, %: 100, 75, 50, 25, 0 (hot idle)

Ambient temperatures, °F: 125, 100, 70, 40, 10, -10, -40, -65

Relative Humidities (R.H.), %: 0, 50, 100

The assessment involved material and energy balance calculations for the powerplant.

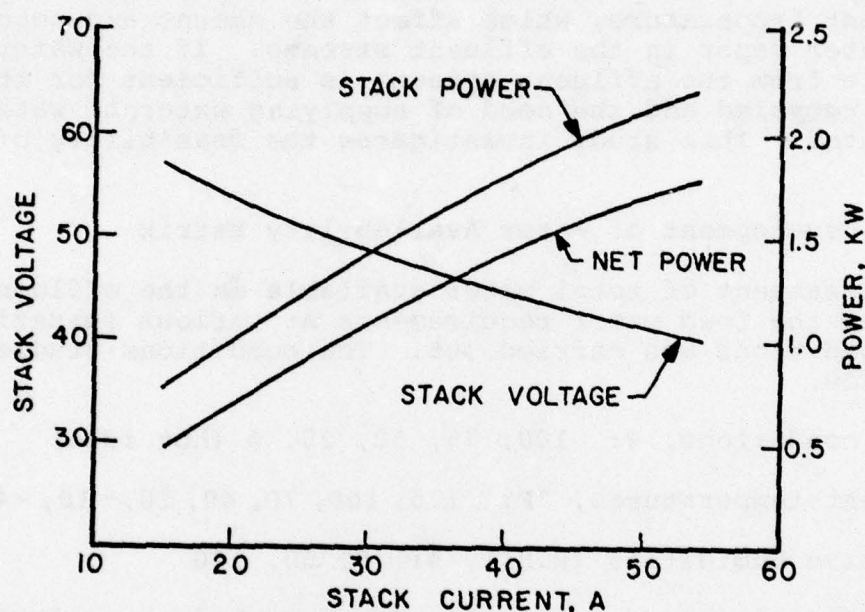
Depending upon the operating and ambient conditions, the powerplant operates in either of the following modes;

(1) At high load conditions, the amount of heat generated in the stack is large. If the ambient temperature is high too, heat losses to the surroundings will be very low. In order to maintain the operating temperature of the fuel cell stack, this extra heat should be removed by passing more process air. Process air requirement in this case will be larger than the stoichiometric and the extra air will serve as a cooling medium.

(2) At low load conditions, heat losses to the surrounding exceed the heat generated in the stack. This requires extra supply of heat to the stack to maintain its desired operating temperature. Part of burner flue gas is used for this purpose. As there is no extra heat to be carried away, process air supplied is close to the stoichiometric requirement.

A computer program was prepared for each operational mode to perform material and energy balance calculations. Estimated stack performance was used in the computations. It is shown in Figure 42.

FIGURE 42
1.5kW INDIRECT METHANOL-AIR
FUEL CELL POWERPLANT PERFORMANCE
(ESTIMATED)



A schematic of powerplant, showing various streams, is presented in Figure 43. The water availability matrix showing amount and concentration of water in the effluent streams, reformer exit stream (RES), and stack anode exhaust (SAE) is presented in Appendix B. Feed water requirements are summarized in Appendix C. Plots showing the effect of ambient air temperature and R.H. on water in feed and effluent streams at various load conditions, were prepared and are presented in Figures 44 to 48. It can be observed that water in the powerplant effluent streams is always more than that required in the feed. Knowing this, the next step should be a search for a suitable water reclaim process which is discussed in the following section.

6.2 Reclaim Process Selection

The various options of reclaiming water from powerplant effluent streams are discussed.

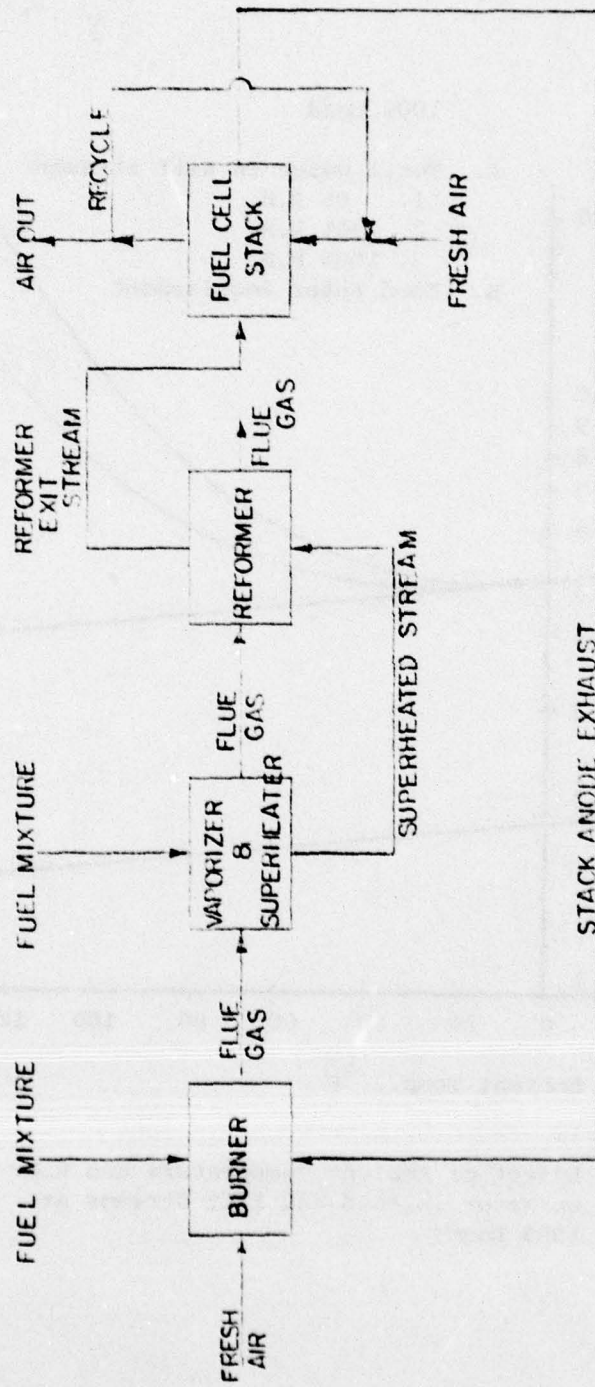


FIG. 43
Schematic of 1.5 kw Indirect Methanol-Air
Fuel Cell Powerplant

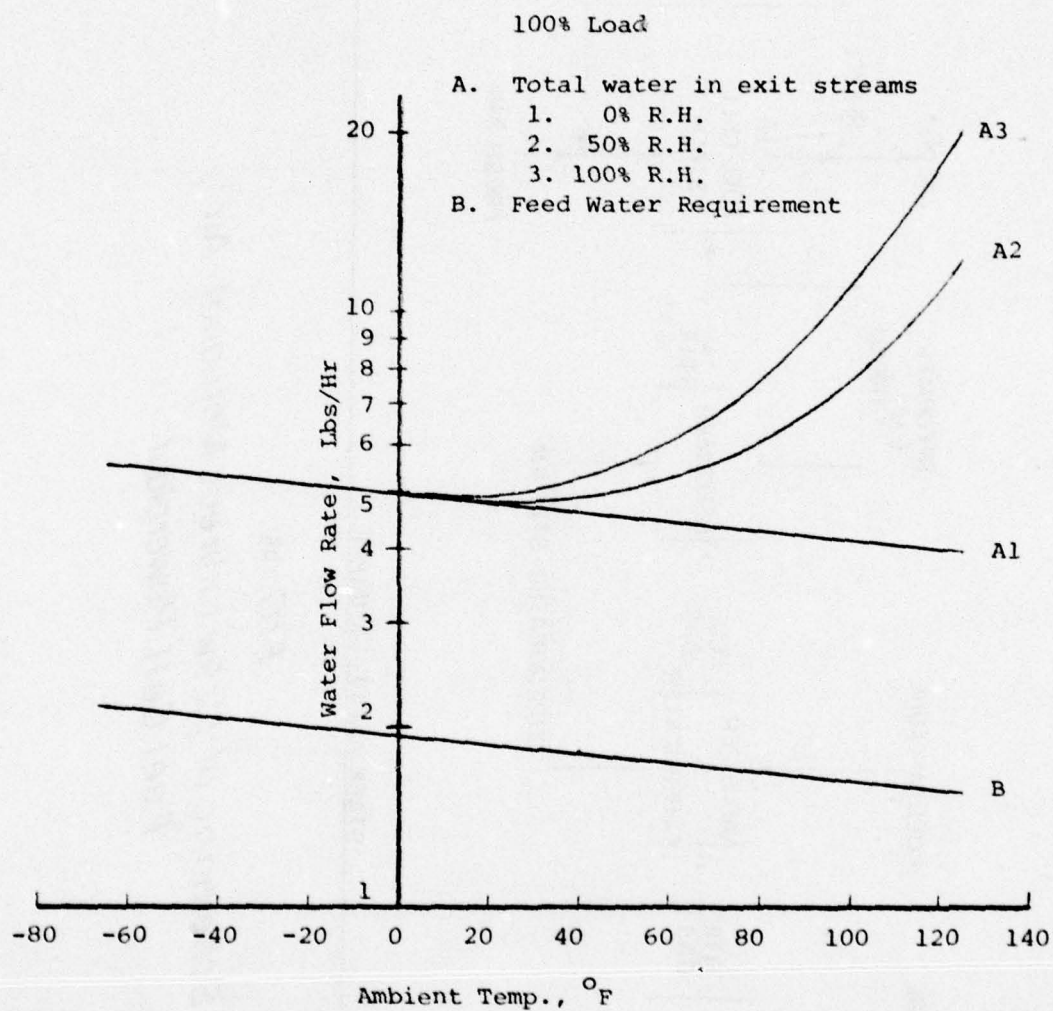


Figure 44 Effect of Ambient Temperature and R.H. on Water in Feed and Exit Streams at 100% Load.

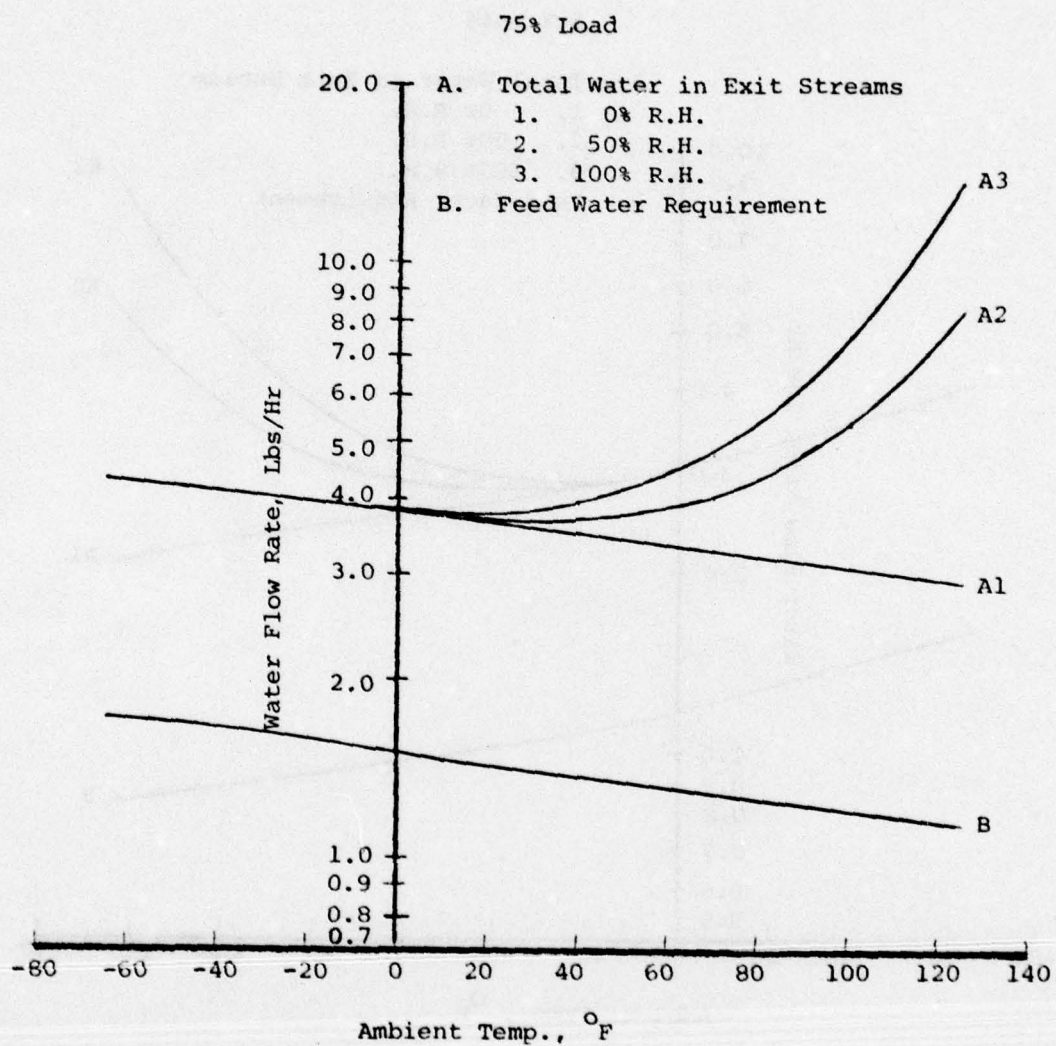


Figure 45 Effect of Ambient Temperature and R.H. on Water in Feed and Exit Streams at 75% Load

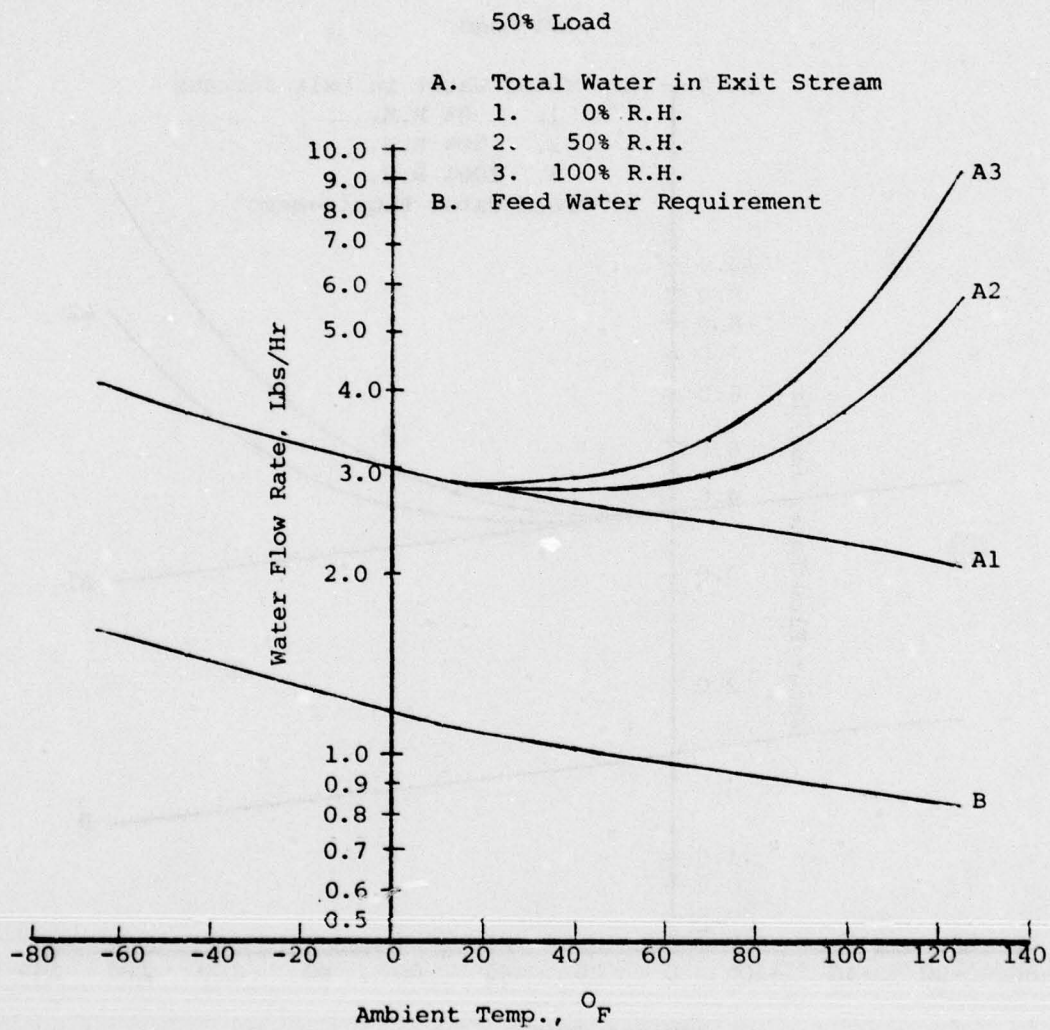


Figure 46 Effect of Ambient Temperature and R.H. on Water in Feed and Exit Streams at 50% Load.

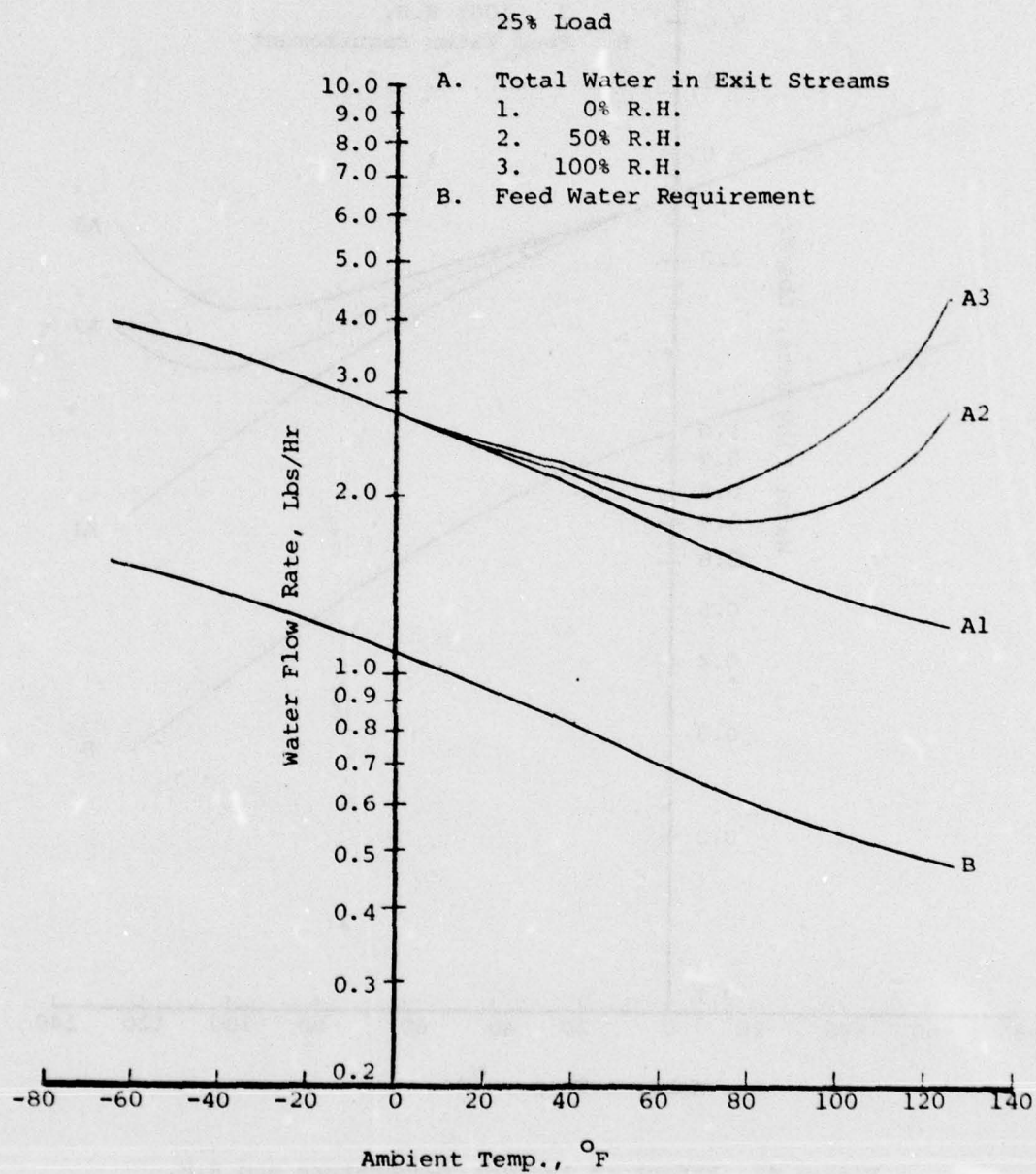


Figure 47 Effect of Ambient Temperature and R.H. on Water in Feed and Exit Streams at 25% Load

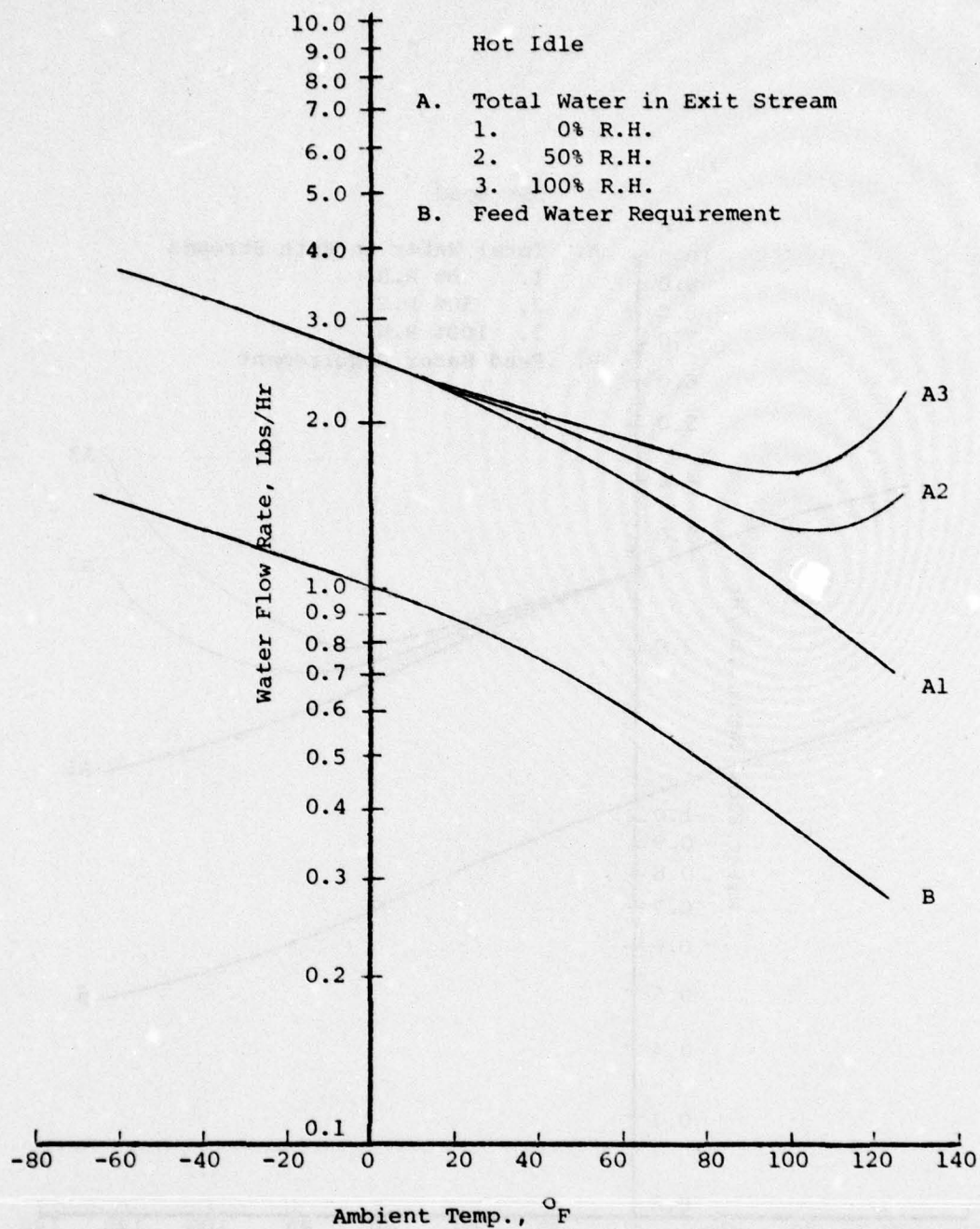


Figure 48 Effect of Ambient Temperature and R.H. on Water in Feed and Exit Streams at Hot Idle Condition

6.2.1 Air-Cooled Exchanger

The effluent stream containing water vapor can be cooled below its dew point, condensing water out. Air cooled exchanger in which ambient air is blown over the finned tubes through which the hot stream is passing (cross flow) can be used for this purpose.

Amounts of water recoverable from powerplant effluent streams under various load conditions for a typical case of ambient air at 70°F and 50% R.H., are presented in Table 12.

TABLE 12

WATER RECOVERY IN AN IDEAL SYSTEM FOR
AMBIENT CONDITIONS OF 50% R.H. & 70°F

% LOAD	FEED WATER lbs/hr	CONDENSED WATER, lb/hr				% WATER RECOVERY
		RFG	BFG	SFG	AIR OUT	
100	1.7106		1.5696		1.6146	186.0
75	1.2907		1.2402		1.2870	195.8
50	0.9533		0.9774		1.0062	207.9
25	0.6403	0.7128		0.0666	0.6678	226.0
Hot Idle	0.5516	0.5652		0.3006	0.3492	220.3

Exchanger area was assumed to be infinite. Feed water requirements and the percentage water recovery based on this are also presented to show the attractiveness of this option. A hundred percent water recovery means recoverable water is exactly equal to water required in the feed. For low load cases, burner flue gas (BFG) is split into reformer flue gas (RFG) and stack flue gas (SFG).

6.2.2 High Pressure Condensation in Air Cooled Exchanger

Pressures higher than atmospheric enhance condensation of water. The liquid fuel mixture can be pressurized above atmospheric pressure (approximately 5 atmospheres) before entering the reformer, and water vapor in the reformer product gas can be condensed in an air cooled exchanger. The reformer product gas leaving the exchanger can then be throttled down to atmospheric pressure, before entering the stack anode side.

Thermodynamic equilibrium calculations show that conversion of methanol at 400°F changes from 99.97% at 1 atmosphere to 99.15% at 5 atmospheres. Hence, composition of reformer exit stream (RES) changes very little. The dew point of the fuel mixture (56.52 mole % methanol) at 5 atmosphere total pressure is 270°F. Hence, reactants will be a vapor at the reaction temperature of 400°F. The amount of water condensed increases from 0.2592 lbs. at 1 atmosphere to 0.3528 lbs. at 5 atmospheres for a typical case of 100% load, 70°F ambient temperature and 50% R.H. Infinite exchanger area was assumed. The gain in water recovered is very small (0.0936 lbs.). This is because the total amount of water in the RES itself is very low. Pumping work required in compression, assuming 50% pump efficiency, is 0.41 watts.

Even though this option reduces the size of reformer and exchanger and it requires little additional energy for pumping, it does not look attractive because of the low gain in recoverable water.

6.2.3 Spray Chamber or Packed Tower

Water vapor can be absorbed by some liquid chemicals. A spray chamber or a packed tower can be used for this purpose.

The simplest spray absorber consists of an empty chamber into which liquid is sprayed at the top and gas is introduced at the bottom. Such a unit has the advantage of very low pressure drop and inexpensive construction. Because of mixing of the gas within the chamber and entrainment of fine spray droplets, spray chambers are unsuitable where true countercurrent action is needed. A spray chamber closely approaches the performance of a packed tower for very short heights (of the order of 26 inches).⁽⁶⁾

The packed tower consists of an equipment filled with packing material up to a certain level. Liquid is fed from the top and gas is introduced from the bottom. The packing material provides larger gas-liquid contact surface area to aid in heat and mass transfer between the two phases. The larger the gas-liquid contact area, the lower the height of the tower required but the higher the pressure drop through the equipment.

Separation of water from the absorbent liquid offers problems and increases the system complexity in both cases - spray chamber and packed tower. Hence, this alternative was discarded from further study.

6.2.4 Bed of Granular Material (Solid Desiccants)

Water vapor can be absorbed or adsorbed by suitable solids and then recovered by heating the solids during their regeneration. Depending upon the mechanism of water separation, solids can be classified into two types.

(1) Absorbents: Water is absorbed by the chemical reaction between water and solid. Materials such as CaCl_2 , LiCl , CaO , BaO , $\text{Mg}(\text{ClO}_4)_2$, CaSO_4 , P_2O_5 , NaOH are common water absorbents. Each of the above has at least one disadvantage. CaO and BaO form insoluble carbonates in atmospheres containing CO_2 and thus, greatly limit water absorbing capacity. Magnesium perchlorate and lithium chloride are deliquescent, causing serious practical problems such as bed deterioration and water drippage. Some of the materials are highly reactive, and their use requires careful control of trace contaminants in the streams from which water is to be recovered. There is no regeneration possible in cases of CaCl_2 , P_2O_5 and NaOH . CaO requires a very high temperature of 1832°F for regeneration.

(2) Adsorbents: Water is adsorbed because of physical attraction of water molecules to the surface of solid. Capillary action is involved with some materials. Silica gel, activated alumina, and molecular sieves are the three most applicable adsorbents. Each adsorbs other gases, particularly CO_2 , in addition to water vapor. These materials are inert and have good structural properties. Their major limitation for long-term usage arises from the possibility of surface poisoning as the result of adsorption of high molecular weight compounds or surface deactivation during regeneration heating cycles. Adsorptive capacity of molecular sieves decreases by one-third over approximately 200 cycles.⁽⁷⁾ For these materials, water capacity decreases with increase in temperature. Molecular sieves have higher water capacity at low water vapor pressures than either silica gel or alumina. Minimum regeneration temperature of silica gel is about 250°F . Because of their high water affinity, molecular sieves and activated alumina require regeneration temperatures between 300°F and 600°F .

Water vapor can be absorbed or adsorbed at the temperature of effluent streams (approximately 300°F) and then recovered at a higher temperature. The weight of 0.7 density silica gel bed was computed for a typical case of 100% load, 70°F ambient temperature and 50% R.H. to be 12.2 lbs. Maximum weight of the bed required would be 15.5 lbs. Weight of the bed is high because of low water capacity at low temperatures. This approach is deemed unattractive.

6.2.5 Direct Contact With Methanol

Liquid methyl alcohol will absorb water vapor at temperatures of 300°F . This concept can be used to reclaim water from the powerplant effluent streams. Some of the methanol is vaporized in the hot gas stream. This methanol can be condensed and recovered by indirect heat exchange with ambient air. This requires the use of an air cooled heat exchanger. Recovery is a function of dew point and at the temperatures involved, would not be complete. This option was not deemed practical or superior to just directly condensing water vapor. The use of an air-cooled exchanger to directly condense water from the powerplant

effluent stream proves to be the most practical method of recovering water. Therefore, this concept will be further examined.

The water condensed in the air-cooled exchanger should be mixed immediately with methanol in order to prevent the freezing of the reclaimed water at temperatures below 32°F. A water recovery system was designed for this purpose. A schematic of the water recovery system is presented in Figure 49.

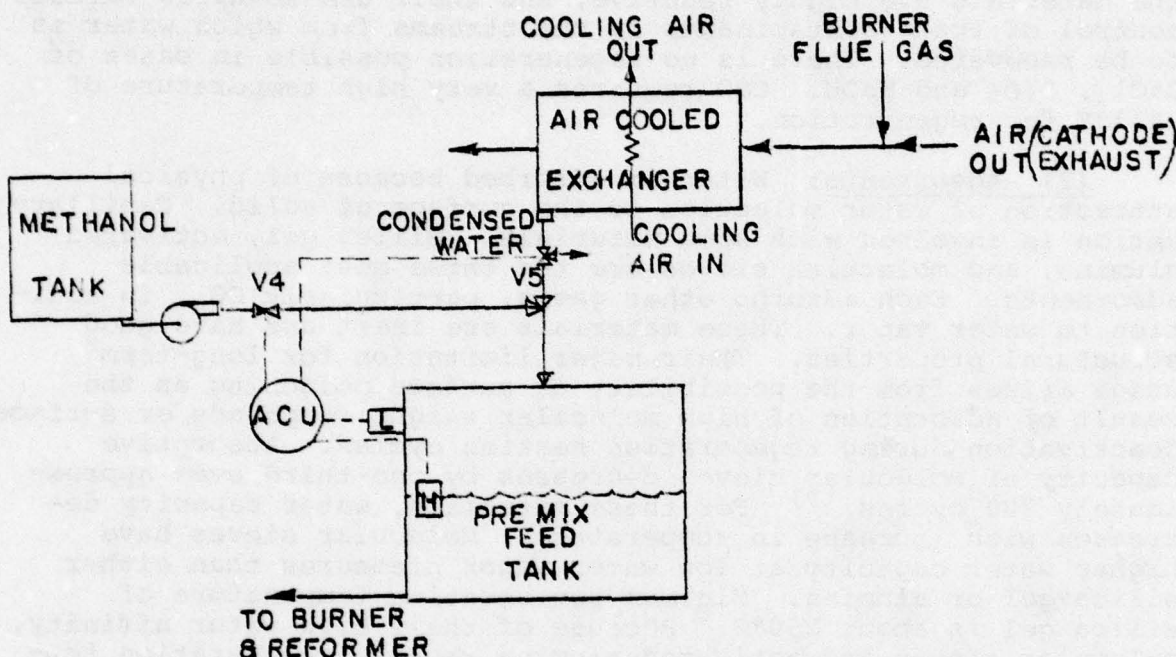
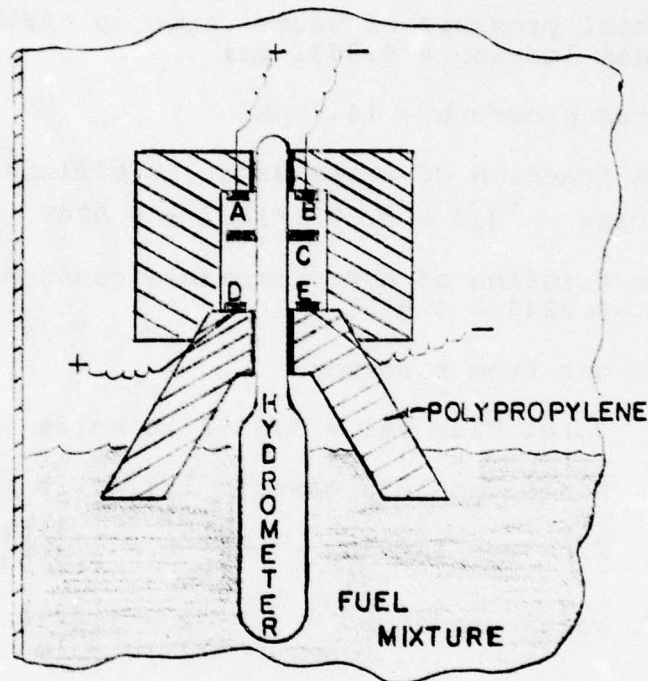


FIGURE 49

SCHEMATIC OF WATER RECOVERY SYSTEM

As the level of the feed mix in the pre-mix holding tank falls, level switch (L) signals the automatic control unit (ACU). The ACU actuates the three-way valve (V5) which allows condensed water to flow into the pre-mix feed tank. Water to methanol molar ratio of 1.3 is maintained by controlling the specific gravity of mixture at the correct value. Specific gravity of the mixture is measured by a hydrometer (H). A detailed schematic of the hydrometer set up is given in Figure 50. As water from the exchanger flows into the pre-mix feed tank, specific gravity of the mixture increases. As a result hydrometer rises. When the specific gravity reaches the upper allowable limit, the conductive ring (c) touches the upper pair of contacts (A and B). A signal is sent to the ACU which opens the valve V4 in the methanol line allowing methanol to flow into the pre-mix feed tank. As the specific gravity decreases, the hydrometer falls, but the valve V4 still remains open. When the specific gravity reaches the lower allowable limit, conductive ring touches the lower pair of contacts (D and E). The control circuit is closed and a

FIGURE 50
SCHEMATIC OF HYDROMETER
SET-UP



signal is sent to ACU which closes the valve V4. When the mixture level in the tank reaches a desired height, the level switch senses it and operates a 3-way valve V5, directing the water flow from the exchanger to dump.

Thus both the required functions of maintaining the mixture level below the maximum specified height and maintaining the water to methanol molar ratio close to 1.3 - are performed.

6.3 Water Balance Cross Plot

For the specified water recovery system, the percentage water recovery for all ambient and load conditions was computed under the assumption of 100% component and system efficiency or infinite exchanger area. The above assumption implies that effluent streams were cooled down to the temperature of ambient air available for cooling. The amount of water condensed is the maximum possible for the respective conditions. Percentage water recovery was defined on the basis of feed water requirement. A hundred percent water recovery means water condensed is exactly equal to the water required in the feed to the reformer and burner. A sample calculation for a typical case of 100% load, 50% R.H., and 70°F ambient temperature is presented.

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ENERGY RESEARCH CORP DANBURY CONN
1.5KW METHANOL FUEL CELL POWERPLANT.(U)
APR 78 S G ABENS, M LAMBRECH, P MARCHETTI

F/G 10/2

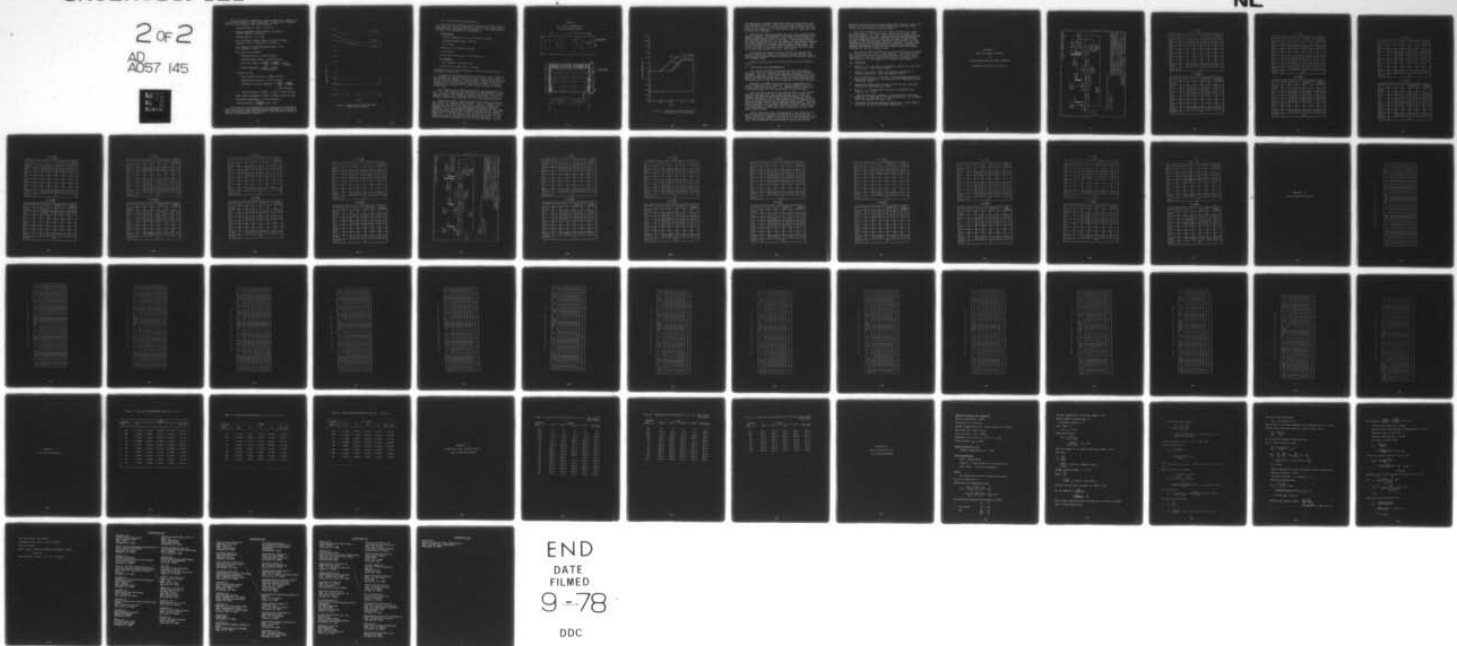
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Both the effluent streams are treated separately, though they can be mixed together. Each stream when it leaves the condenser will be in equilibrium with liquid water at 70°F.

vapor pressure at 70°F = 0.3631 psi

∴ partial pressure of water vapor in effluent stream leaving = 0.3631 psi

system pressure = 14.7 psi

∴ mole fraction of water vapor in effluent stream leaving = $y_{H_2O} = 0.3631/14.7 = 0.0247$

mole fraction of noncondensable gases = y_{NC}
= $1 - 0.0247 = 0.9753$

Flue gas from reformer:

Total Flue gas = 1.5392 lb moles

Noncondensable gases = 1.4141 lb moles

Flue gas leaving = $\frac{1.4161}{y_{NC}} = \frac{1.4161}{0.9753} = 1.4520$ lb moles

∴ Water condensed = $1.5392 - 1.4520$
= 0.0872 lb mole

Process Air Out:

Total process air out = 3.8089 lb moles

Noncondensable gases = 3.6273 lb moles

Process air leaving condenser = $\frac{3.6273}{y_{NC}} = \frac{3.6273}{0.9753}$
= 3.7192 lb moles

Water condensed = $3.8089 - 3.7192 = 0.0897$ lb mole

Total water condensed = $0.0872 + 0.0897 = 0.1769$ lb mole

Feed water requirement = 0.0951 lb moles

% water recovery = $\frac{0.1769}{0.0951} \times 100 = 186$

The results of the computations are summarized in Appendix D. Cross plots on the water availability matrix showing all the operating and ambient conditions under which complete water balance is possible are presented in Figure 51.

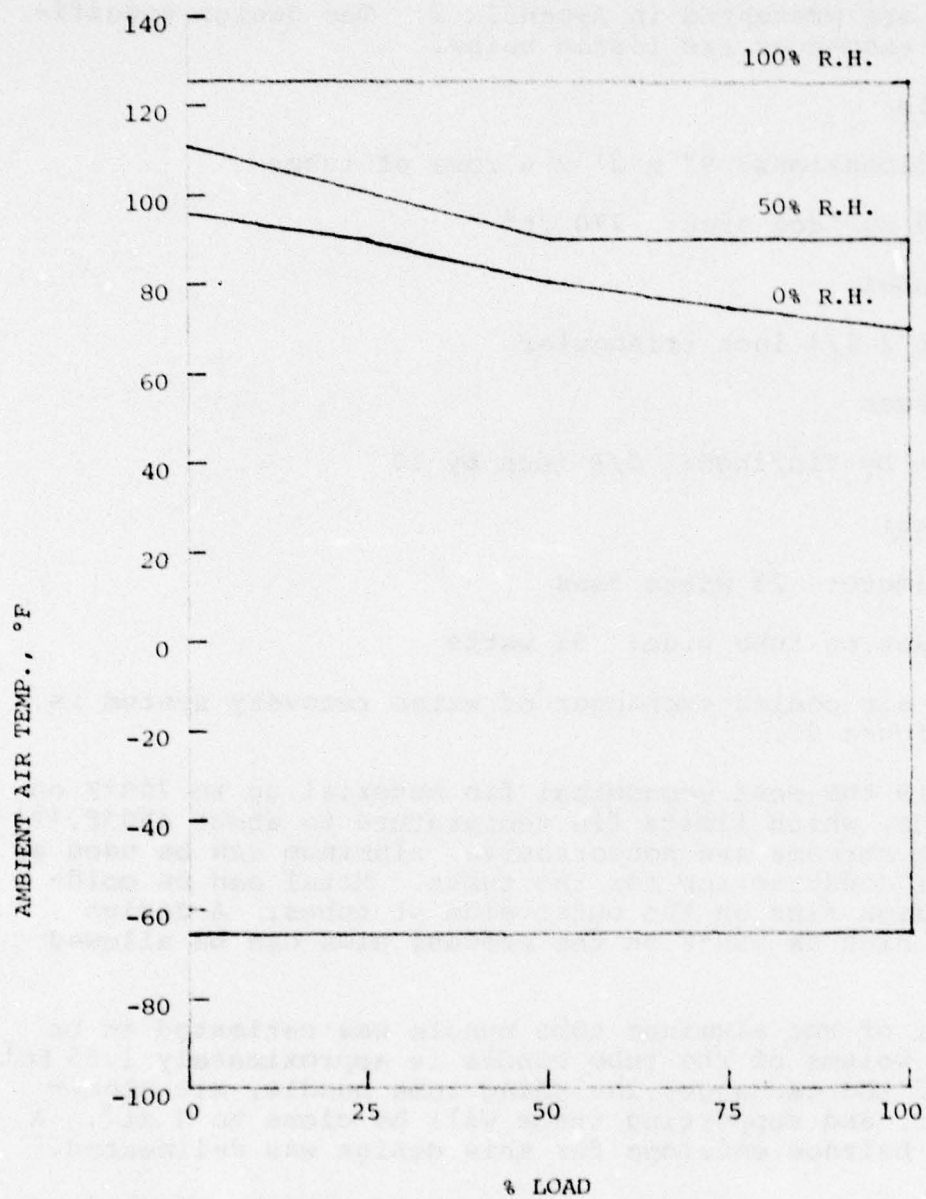


FIGURE 51: COMPLETE WATER BALANCE ENVELOPES
(100% System Efficiency)

6.4 Process Design Considerations

An air cooled exchanger was designed for a typical case of 100% load, 70°F ambient temperature, and 50% R.H. The design calculations⁽⁴⁾ are presented in Appendix E. The design specifications of the exchanger are listed below.

Tube Bundle:

Linear dimensions: 9" x 2' x 6 rows of tubes

Extended surface area: 270 ft²

1" OD tubes

Tube pitch 2 1/4 inch triangular

6 tube passes

Fin height by fin/inch: 5/8 inch by 10

Air blowers:

2-8" diameter, 23 watts fans

blower power on tube side: 51 watts

A schematic of air cooled exchanger of water recovery system is presented in Figure 52.

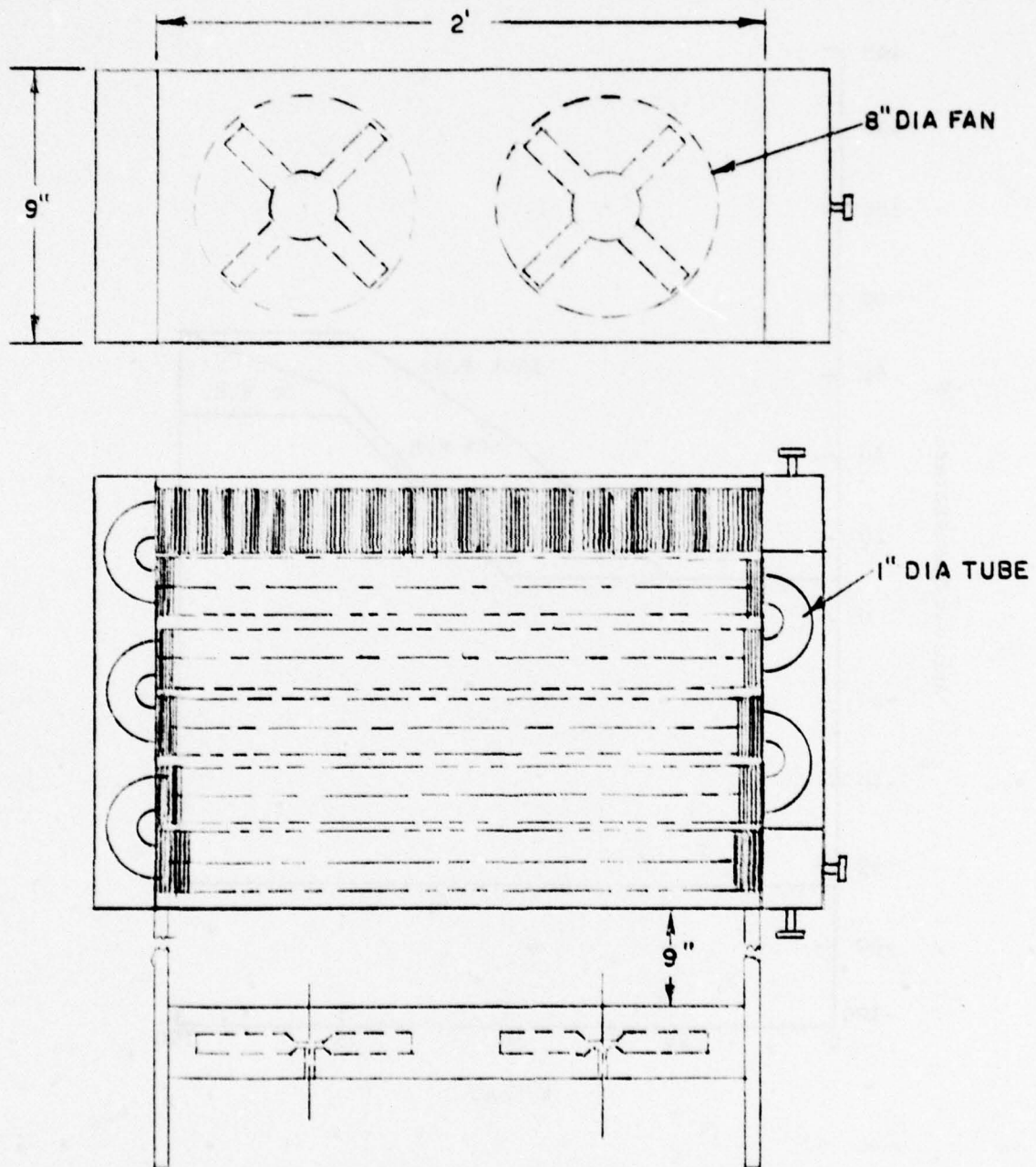
Aluminum is the most economical fin material up to 750°F on the process side, which limits fin temperature to about 450°F.⁽⁶⁾ As the effluent streams are noncorrosive, aluminum can be used as the material of construction for the tubes. Metal can be cold-extruded into high fins on the outer side of tubes. A design temperature as high as 550°F on the process side can be allowed in this case.

The weight of the aluminum tube bundle was estimated to be 11.2 lbs. The volume of the tube bundle is approximately 1.55 ft³. Total volume of the exchanger including tube bundle, air plenum chamber, blower, and supporting frame will be close to 3 ft³. A complete water balance envelope for this design was delineated.

Using this design, various operating and ambient conditions were tested for complete water balance. ΔT_m is a function of U_x . So by trial and error, the value of U_x required to handle the required heat load with the designed heat transfer area was computed. Using the designed exchanger dimensions and flow rates, overall transfer coefficient available was calculated. Complete water balance envelopes for 0%, 50%, and 100% R.H. are shown in Figure 53. It can be observed that the envelope sizes are considerably smaller than those at 100% system efficiency. It becomes difficult to recover water as the load decreases. As the

FIGURE 52

AIR COOLED EXCHANGER FOR
WATER RECOVERY SYSTEM



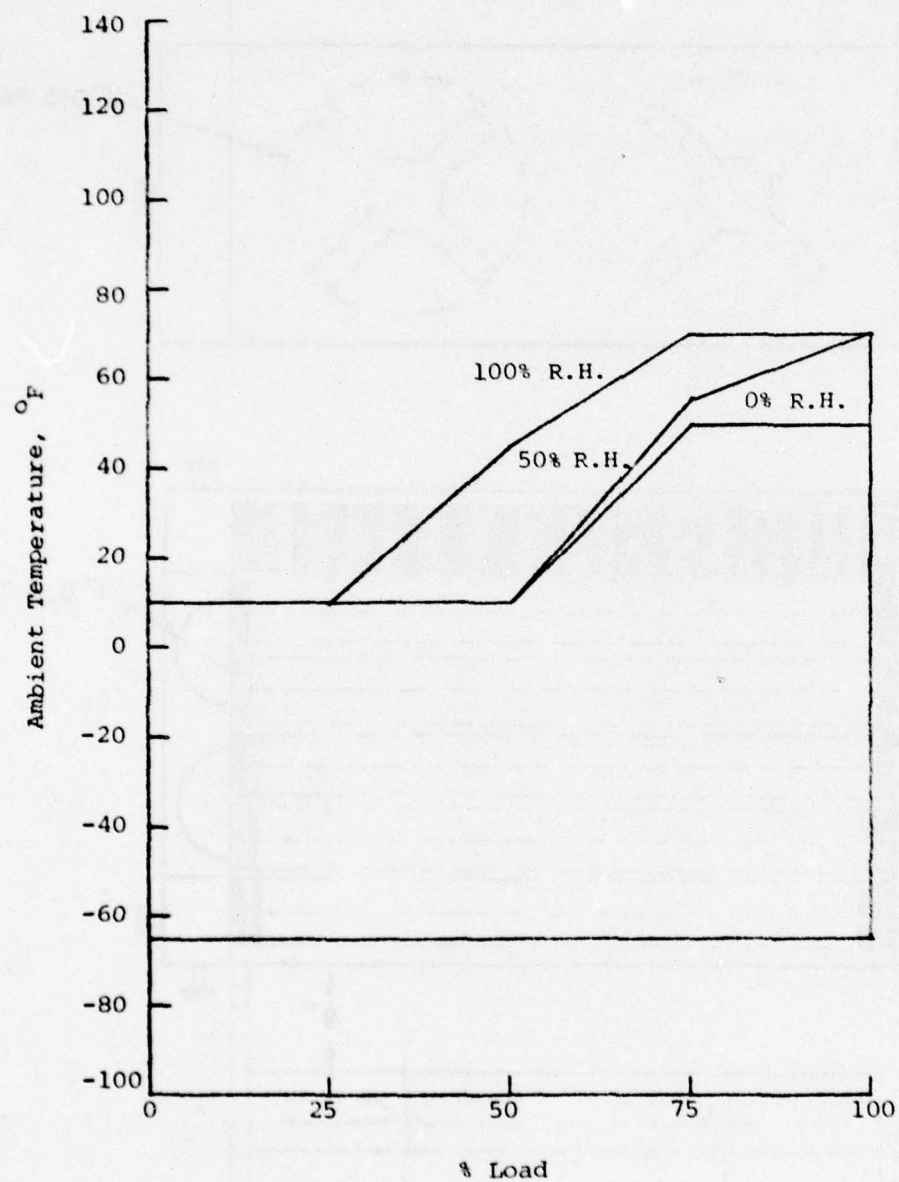


Figure 53 Complete Water Balance Envelopes for the Designed Air Cooled Exchanger

load decreases, effluent stream flow rates decrease; hence, the available heat transfer coefficient decreases, requiring higher heat transfer area. Since heat transfer area is fixed, the water recovery is incomplete. As expected, as the R.H. increases, the envelope size increases.

Efforts were made to increase the size of the complete water balance envelope. An exchanger was designed for 100% load, 80°F ambient temperature and 50% R.H. case. The overall transfer coefficient was higher, 0.96 in this case. The extended surface area required was 189 ft², but the number of tube passes increased to 8 which resulted in higher pressure drop through tubes. The power requirement on the tube side increased to 236 watts, and on the air side, it increased to 60 watts making the total parasitic power requirement very high - 296 watts.

Decreasing the number of passes reduces the overall heat transfer coefficient requiring a larger extended surface area resulting in increased linear dimensions of the exchanger beyond the allowable limit.

Larger envelopes can be obtained at the cost of parasitic power.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The indirect methanol powerplant generally performed in accordance with the concepts developed on this and on earlier programs. The fuel conditioning subsystem performed well, with methanol conversion at over 99%. Fuel cell performance was somewhat lower than projected, but this was at least partially due to maintenance of a conservative temperature level for the stack.

Response to sudden load increases was instantaneous for current steps under 10-15 amperes. Larger stepwise current increases produced "squatting", i.e., voltage drops in the stack sufficiently large to initiate shutdown of the powerplant.

This condition appears to be characteristic of the present indirect methanol fuel cell system design, but a number of measures for improving response may be suggested. One such measure evaluated on this project involved increasing the fuel feed to the reformer and to the reformer burner following an upward load change larger than 10 amperes stack current. This approach appeared to be at least partially effective, but difficulties with making it compatible with the automatic control logic were encountered, and the deliverable powerplant did not incorporate this feature.

Difficulties were also encountered with the control of reformer fuel flow in response to variations in stack current. This situation was caused by the effect of stray electrical noise signals from other system components on the current-sensing circuit. This difficulty can be overcome by redesigned system

grounding and more rigorous noise suppression methods. Recent advances in microprocessor technology make this practical alternative for the controller circuit hardware.

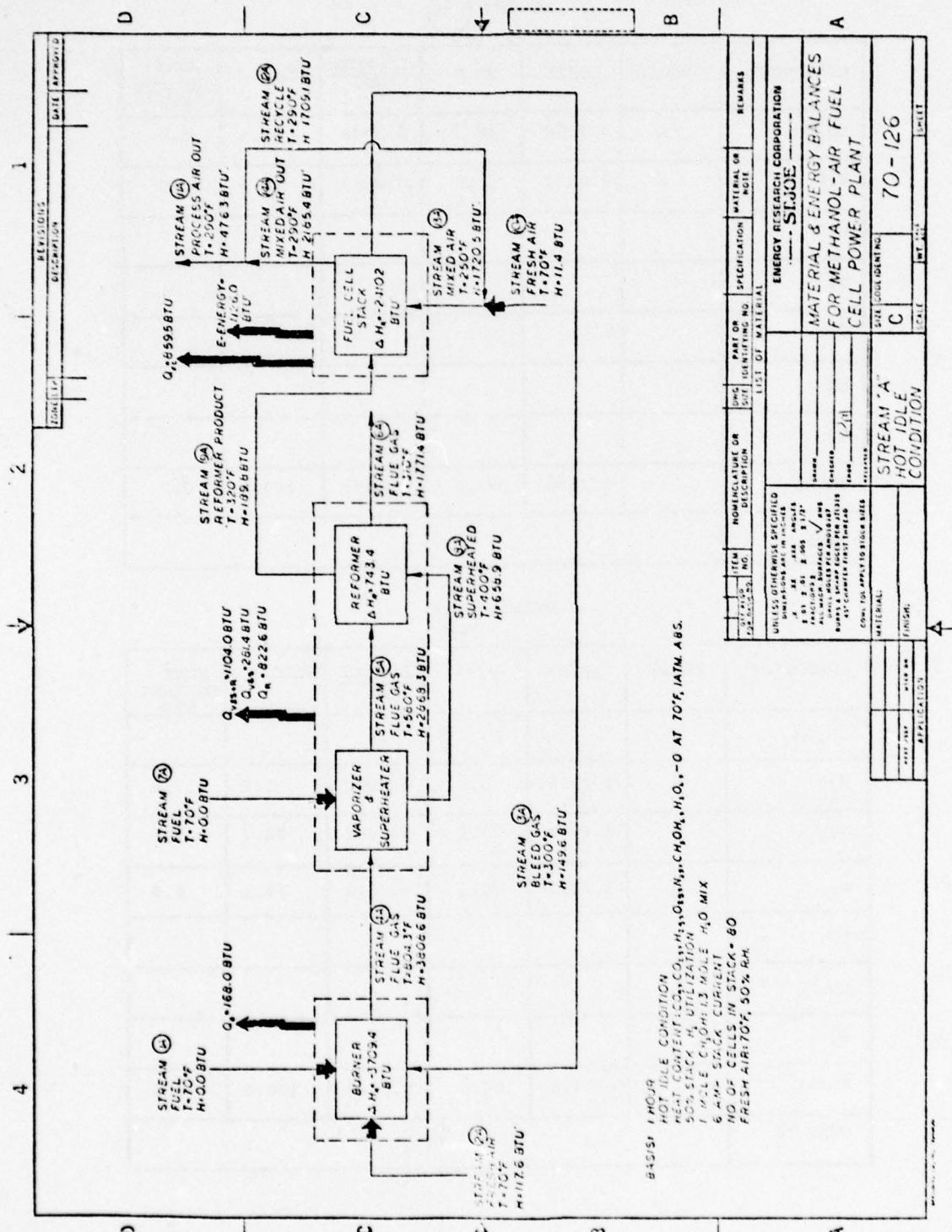
The final powerplant size fell within the 8 cu. ft. target for this project. The final weight, however, was higher than projected (258 vs. 175 lbs). The excess weight resides partially in a considerably oversized reformer which was deemed desirable for this powerplant since it improved response to upward load changes. Other excess weight resides in off-the-shelf ancillary components, such as solenoid valves and plumbing. Finally, much weight reduction can be expected from further stack ancillary hardware development as well as from higher stack load voltage allowing the use of a smaller stack.

The rate of fuel consumption of this powerplant also exceeded the project goals (2.1 vs. 1.2 lbs MeOH/kW). The higher consumption is partly due to a lower than expected fuel cell voltage. Improvement in fuel efficiency should also be achievable by further insulation of the powerplant to minimize heat losses.

8.0 REFERENCES

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APPENDIX A
HEAT and MATERIAL BALANCE
for
1.5KW METHANOL-AIR FUEL CELL GENERATOR
CONTRACT NO. DAAG-53-76-C-0118



STREAM (1A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH	L	0.1280	58.2	0.0040	43.5	0.0
H ₂ O	L	0.0918	41.8	0.0051	56.5	0.0
O ₂						
N ₂						
CO ₂						
CO						
H ₂						
TOTAL		0.2198	100.0	0.0091	100.0	0.0
TEMP. °F	70					

STREAM (2A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.1116	0.8	0.0062	1.2	117.6
O ₂	G	3.4048	23.1	0.1064	20.7	0.0
N ₂	G	11.2392	76.1	0.4014	78.1	0.0
CO ₂						
CO						
H ₂						
TOTAL		14.7556	100.0	0.5140	100.0	117.6
TEMP °F	70					

STREAM (3A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	.0774	11.2	0.0043	11.6	89.5
O ₂						
N ₂						
CO ₂	G	.5676	81.9	0.0129	34.7	28.1
CO	G	.0084	1.2	0.0003	0.7	0.5
H ₂	G	.0394	5.7	0.0197	53.0	31.5
TOTAL		.6928	100.0	0.0372	100.0	149.6
TEMP. °F	300					

STREAM (4A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.7794	5.0	0.0433	7.8	1089.2
O ₂	G	2.8923	18.5	0.0904	16.4	493.4
N ₂	G	11.2392	71.7	0.4014	72.7	2092.8
CO ₂	G	0.7568	4.8	0.0172	3.1	133.2
CO						
H ₂						
TOTAL		15.6682	100.0	0.5523	100.0	3808.6
TEMP °F	804.3					

STREAM (5A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.7794	5.0	0.0433	7.8	1003.9
O ₂	G	2.8928	18.5	0.0904	16.4	336.2
N ₂	G	11.2392	71.7	0.4014	72.7	1439.4
CO ₂	G	0.7568	4.8	0.0172	3.1	88.8
CO						
H ₂						
TOTAL		15.6682	100.0	0.5523	100.0	2868.3
TEMP. °F	580					

STREAM (6A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.7794	5.0	0.0433	7.8	905.4
O ₂	G	2.8928	18.5	0.0904	16.4	154.5
N ₂	G	11.2392	71.7	0.4014	72.7	672.3
CO ₂	G	0.7568	4.8	0.0172	3.1	39.2
CO						
H ₂						
TOTAL		15.6682	100.0	0.5523	100.0	1771.4
TEMP °F	310					

STREAM (7A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH	L	0.4224	57.7	0.0132	43.4	0.0
H ₂ O	L	0.3096	42.3	0.0172	56.6	0.0
O ₂						
N ₂						
CO ₂						
CO						
H ₂						
TOTAL		0.7320	100.0	0.0304	100.0	0.0
TEMP. °F	70					

STREAM (8A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH	G	0.4224	57.7	0.0132	43.4	286.4
H ₂ O	G	0.3096	42.3	0.0172	56.6	372.5
O ₂						
N ₂						
CO ₂						
CO						
H ₂						
TOTAL		0.7320	100.0	0.0304	100.0	658.9
TEMP °F	400					

STREAM (9A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.0774	10.6	0.0043	7.6	90.2
O ₂						
N ₂						
CO ₂	G	0.5676	77.5	0.0129	22.7	30.8
CO	G	0.0084	1.1	0.0003	0.5	0.5
H ₂	G	0.0786	10.8	0.0393	69.2	68.3
TOTAL		0.7320	100.0	0.0568	100.0	189.8
TEMP. °F	320					

STREAM (10A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.0108	.8	0.0006	1.3	11.4
O ₂	G	0.3136	22.9	0.0098	20.5	0.0
N ₂	G	1.0444	76.3	0.0373	78.2	0.0
CO ₂						
CO						
H ₂						
TOTAL		1.3688	100.0	0.0477	100.0	11.4
TEMP °F	70					

STREAM (11A)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.3636	25.8	0.0202	35.1	419.0
O ₂	G	0	0	0	0	0
N ₂	G	1.0444	74.2	0.0373	64.9	57.3
CO ₂						
CO						
H ₂						
TOTAL		1.4080	100.0	0.0575	100.0	476.3
TEMP. °F	290					

STREAM (12A)

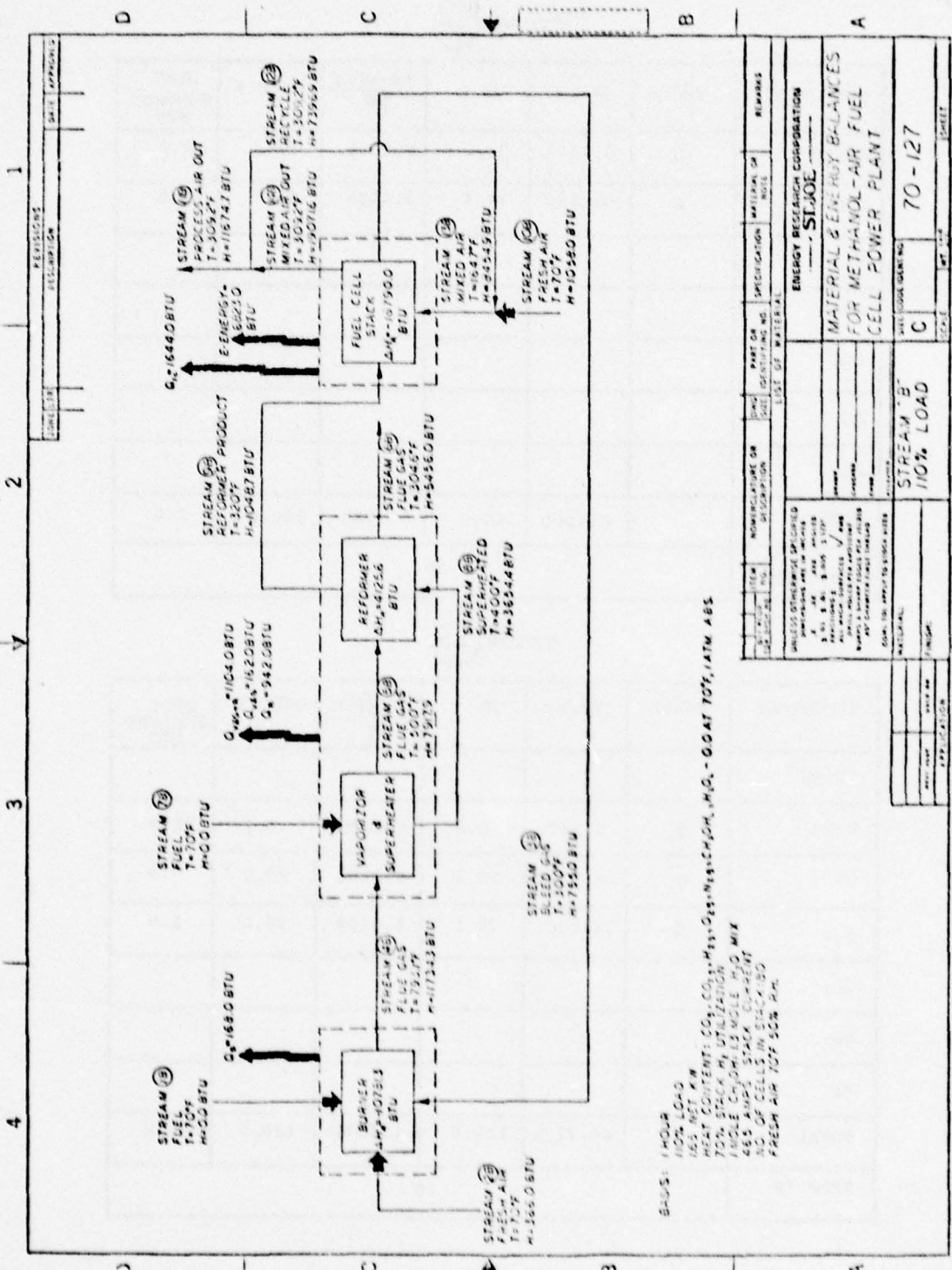
COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	1.3050	25.9	0.0725	35.2	1504.0
O ₂	G	0	0	0	0	0
N ₂	G	3.7408	74.1	0.1336	64.8	205.1
CO ₂						
CO						
H ₂						
TOTAL		5.0458	100.0	0.2061	100.0	1709.1
TEMP °F	290					

STREAM 13A

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	1.3158	20.5	0.0731	28.8	1492.9
O ₂	G	0.3136	4.9	0.0098	3.9	12.5
N ₂	G	4.7852	74.6	0.1709	67.3	215.1
CO ₂						
CO						
H ₂						
TOTAL		6.4146	100.0	0.2538	100.0	1720.5
TEMP. °F	250					

STREAM 14A

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	1.6686	25.9	0.0927	35.2	1923.0
O ₂	G	0	0	0	0	0
N ₂	G	4.7852	74.1	0.1709	64.8	262.4
CO ₂						
CO						
H ₂						
TOTAL		6.4538	100.0	0.2636	100.0	2185.4
TEMP °F	290					



STREAM (1B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH	L	0.2592	57.6	0.0081	43.3	0.0
H ₂ O	L	0.1908	42.4	0.0106	56.7	0.0
O ₂						
N ₂						
CO ₂						
CO						
H ₂						
TOTAL		0.4500	100.0	0.0187	100.0	0.0
TEMP. °F	70					

STREAM (2B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.3474	0.8	0.0193	1.2	366.0
O ₂	G	10.3392	23.1	0.3231	20.8	0.0
N ₂	G	34.0312	76.1	1.2154	78.0	0.0
CO ₂						
CO						
H ₂						
TOTAL		44.7178	100.0	1.5578	100.0	366.0
TEMP °F	70					

STREAM (3 B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.4248	11.3	0.0236	14.5	491.5
O ₂						
N ₂						
CO ₂	G	3.1548	84.0	0.0717	44.2	156.2
CO	G	0.0448	1.2	0.0016	1.0	2.6
H ₂	G	0.1310	3.5	0.0655	40.3	104.7
TOTAL		3.7554	100.0	0.1624	100.0	755.0
TEMP. °F	300					

STREAM (4 B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	2.4336	5.0	0.1352	7.9	3387.5
O ₂	G	8.8768	18.1	0.2774	16.2	1489.6
N ₂	G	34.0312	69.6	1.2154	71.1	6237.4
CO ₂	G	3.5816	7.3	0.0814	4.8	619.8
CO						
H ₂						
TOTAL		48.9232	100.0	1.7094	100.0	11734.3
TEMP °F	793.1					

STREAM (5 B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	2.4336	5.0	0.1352	7.9	3041.9
O ₂	G	8.8768	18.1	0.2774	16.2	863.5
N ₂	G	34.0312	69.6	1.2154	71.1	3664.4
CO ₂	G	3.5816	7.3	0.0814	4.8	348.1
CO						
H ₂						
TOTAL		48.9232	100.0	1.7094	100.0	7917.9
TEMP. °F	500					

STREAM (6 B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	2.4336	5.0	0.1352	7.9	2821.2
O ₂	G	8.8768	18.1	0.2774	16.2	463.4
N ₂	G	34.0312	69.6	1.2154	71.1	1990.0
CO ₂	G	3.5816	7.3	0.0814	4.8	181.4
CO						
H ₂						
TOTAL		48.9232	100.0	1.7094	100.0	5456.0
TEMP °F	304.6					

STREAM (7 B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH	L	2.3456	57.8	0.0733	43.5	0.0
H ₂ O	L	1.7154	42.2	0.0953	56.5	0.0
O ₂						
N ₂						
CO ₂						
CO						
H ₂						
TOTAL		4.0610	100.0	0.1686	100.0	0.0
TEMP. °F	70					

STREAM (8 B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH	G	2.3456	57.8	0.0733	43.5	1590.5
H ₂ O	G	1.7154	42.2	0.0953	56.5	2063.9
O ₂						
N ₂						
CO ₂						
CO						
H ₂						
TOTAL		4.0610	100.0	0.1686	100.0	3654.4
TEMP °F	400					

STREAM (9B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	0.4248	10.5	0.0236	7.5	495.5
O ₂						
N ₂						
CO ₂	G	3.1548	77.7	0.0717	22.7	171.0
CO	G	0.0448	1.1	0.0016	0.5	2.8
H ₂	G	0.4366	10.7	0.2183	69.3	379.4
TOTAL		4.0610	100.0	0.3152	100.0	1048.7
TEMP. °F	320					

STREAM (10B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	1.0044	0.8	0.0558	1.2	1058.0
O ₂	G	29.8400	23.1	0.9325	20.7	0.0
N ₂	G	98.2184	76.1	3.5078	78.1	0.0
CO ₂						
CO						
H ₂						
TOTAL		129.0628	100.0	4.4961	100.0	1058.0
TEMP °F	70					

STREAM (11)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	3.7548	2.9	0.2086	4.6	4060.3
O ₂	G	27.3952	21.2	0.8561	18.7	1457.9
N ₂	G	98.2184	75.9	3.5078	76.7	5856.5
CO ₂						
CO						
H ₂						
TOTAL		129.3684	100.0	4.5725	100.0	11674.7
TEMP. °F	309.2					

STREAM (12)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	2.3580	2.9	0.1310	4.5	2738.4
O ₂	G	17.4144	21.1	0.5442	18.7	926.9
N ₂	G	62.5800	76.0	2.2350	76.8	3731.6
CO ₂						
CO						
H ₂						
TOTAL		82.3524	100.0	2.9102	100.0	7396.9
TEMP °F	309.2					

STREAM (13B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	3.3624	1.6	0.1868	2.5	3683.0
O ₂	G	47.2544	22.3	1.4767	19.9	981.9
N ₂	G	160.7984	76.1	5.7428	77.6	3790.0
CO ₂						
CO						
H ₂						
TOTAL		211.4152	100.0	7.4063	100.0	8454.9
TEMP. °F	164.7					

STREAM (14B)

COMPONENT	PHASE	LB/HR	WT %	LB-MOLE HR	MOLE %	HEAT CONTENT BTU
CH ₃ OH						
H ₂ O	G	6.1128	2.9	0.3396	4.5	7098.7
O ₂	G	44.8096	21.2	1.4003	18.7	2384.8
N ₂	G	160.7984	75.9	5.7428	76.8	9588.1
CO ₂						
CO						
H ₂						
TOTAL		211.7208	100.0	7.4827	100.0	19071.6
TEMP °F	309.2					

Appendix: B
Water Availability Matrix

Table B1 Water Availability Matrix - 0% R.H., 100% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	1.4697	6.3	2.4380	2.3	3.9077	0.3766	7.5	0.3766	14.5
100	1.6716	6.5	2.4380	2.8	4.1096	0.3766	7.5	0.3766	14.5
90	1.7498	6.6	2.4380	3.1	4.1878	0.3766	7.5	0.3766	14.5
80	1.8289	6.8	2.4380	3.3	4.2669	0.3766	7.5	0.3766	14.5
70	1.9048	6.9	2.4380	3.5	4.3428	0.3766	7.5	0.3766	14.5
40	2.1559	7.2	2.4380	4.4	4.5939	0.3766	7.5	0.3766	14.5
10	2.4027	7.5	2.4380	5.4	4.8407	0.3766	7.5	0.3766	14.5
-10	2.5725	7.7	2.4380	6.2	5.0105	0.3766	7.5	0.3766	14.5
-40	2.8337	8.0	2.4380	7.6	5.2717	0.3766	7.5	0.3766	14.5
-65	3.0567	8.3	2.4380	9.0	5.4947	0.3766	7.5	0.3766	14.5

Table B2 Water Availability Matrix - 0% R.H., 75% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAR LBS/HR	MOLE %
125	1.1123	6.3	1.7753	2.6	2.8876	0.2742	7.5	0.2742	14.5
100	1.2915	6.6	1.7753	3.3	3.0668	0.2742	7.5	0.2742	14.5
90	1.3616	6.7	1.7753	3.6	3.1369	0.2742	7.5	0.2742	14.5
80	1.4326	6.8	1.7753	3.9	3.2079	0.2742	7.5	0.2742	14.5
70	1.5015	6.9	1.7753	4.3	3.2768	0.2742	7.5	0.2742	14.5
40	1.7265	7.3	1.7753	5.7	3.5018	0.2742	7.5	0.2742	14.5
10	1.9495	7.6	1.7753	7.7	3.7248	0.2742	7.5	0.2742	14.5
-10	2.1029	7.8	1.7753	9.5	3.8782	0.2742	7.5	0.2742	14.5
-40	2.3389	8.1	1.7753	13.5	4.1142	0.2742	7.5	0.2742	14.5
-65	2.5406	8.4	1.7753	19.2	4.3159	0.2742	7.5	0.2742	14.5

Table B3 Water Availability Matrix - 0% R.H., 50% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN SHE LBS/HR	MOLE %	H ₂ O IN SHE LBS/HR	MOLE %
125	0.8251	6.3	1.2427	2.9	2.0678	0.1920	7.5	0.1920	14.5
100	0.9860	6.7	1.2427	4.0	2.2287	0.1920	7.5	0.1920	14.5
90	1.0497	6.8	1.2427	4.6	2.2924	0.1920	7.5	0.1920	14.5
80	1.1143	6.9	1.2427	5.2	2.3570	0.1920	7.5	0.1920	14.5
70	1.1774	7.0	1.2427	6.0	2.4201	0.1920	7.5	0.1920	14.5
40	1.3814	7.4	1.2427	9.7	2.6241	0.1920	7.5	0.1920	14.5
10	1.5854	7.7	1.2427	18.9	2.8281	0.1920	7.5	0.1920	14.5
-10	1.7265	7.9	1.2427	34.7	3.0950	0.1920	7.5	0.1920	14.5
-40	1.9430	8.2	1.2427	34.7	3.6220	0.1920	7.5	0.1920	14.5
-65	2.1274	8.5	1.2427	34.7	4.0770	0.1920	7.5	0.1920	14.5

Table B4 Water Availability Matrix - 0% R.H., 25% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	0.5219	6.5	0.6805	4.0	1.2024	0.1051	7.5	0.1051	14.5
100	0.6838	6.3	0.6805	7.8	1.3643	0.1226	7.5	0.1226	12.8
90	0.7418	6.5	0.6805	11.5	1.4223	0.1226	7.5	0.1226	12.8
80	0.8008	6.6	0.6805	20.0	1.4813	0.1226	7.5	0.1226	12.8
70	0.8631	6.8	0.6805	34.7	1.6249	0.1226	7.5	0.1226	12.8
40	1.0554	7.2	0.6805	34.7	2.1068	0.1226	7.5	0.1226	12.8
10	1.2444	7.6	0.6805	34.7	2.6046	0.1226	7.5	0.1226	12.8
-10	1.3729	7.8	0.6805	34.7	2.9478	0.1226	7.5	0.1226	12.8
-40	1.5632	8.2	0.6805	34.7	3.4792	0.1226	7.5	0.1226	12.8
-65	1.7382	8.5	0.6805	34.7	3.9372	0.1226	7.5	0.1226	12.8

Table B5 Water Availability Matrix - 0% R.H., Hot Idle

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	0.3464	6.7	0.3551	5.0	0.7015	0.0548	7.5	0.0548	14.5
100	0.5094	6.3	0.3551	34.7	0.9468	0.0768	7.5	0.0768	11.5
90	0.5680	6.5	0.3551	34.7	1.0956	0.0768	7.5	0.0768	11.5
80	0.6257	6.7	0.3551	34.7	1.2472	0.0768	7.5	0.0768	11.5
70	0.6820	6.8	0.3551	34.7	1.4002	0.0768	7.5	0.0768	11.5
40	0.8563	7.3	0.3551	34.7	1.8790	0.0768	7.5	0.0768	11.5
10	1.0310	7.6	0.3551	34.7	2.3740	0.0768	7.5	0.0768	11.5
-10	1.1504	7.9	0.3551	34.7	2.7149	0.0768	7.5	0.0768	11.5
-40	1.3340	8.2	0.3551	34.7	3.2424	0.0768	7.5	0.0768	11.5
-65	1.4912	8.5	0.3551	34.7	3.6967	0.0768	7.5	0.0768	11.5

Table B6 Water Availability Matrix - 50% R.H., 100% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	2.8774	12.4	9.2359	8.9	12.1133	0.3766	7.5	0.3766	14.5
100	2.4198	9.5	5.1548	6.0	7.5746	0.3766	7.5	0.3766	14.5
70	2.2161	8.0	3.2690	4.8	5.4851	0.3766	7.5	0.3766	14.5
40	2.2688	7.6	2.6628	4.8	4.9316	0.3766	7.5	0.3766	14.5
10	2.4333	7.6	2.4842	5.5	4.9175	0.3766	7.5	0.3766	14.5
-10	2.5837	7.8	2.4522	6.2	5.0359	0.3766	7.5	0.3766	14.5
-40	2.8357	8.0	2.4400	7.6	5.2757	0.3766	7.5	0.3766	14.5
-65	3.0571	8.3	2.4383	9.0	5.4954	0.3766	7.5	0.3766	14.5

Table B7 Water Availability Matrix - 50% R.H., 75% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	2.1721	12.4	6.2547	9.2	8.4268	0.2742	7.5	0.2742	14.5
100	1.8655	9.6	3.5038	6.4	5.3693	0.2742	7.5	0.2742	14.5
70	1.7449	8.1	2.2717	5.5	4.0166	0.2742	7.5	0.2742	14.5
40	1.8161	7.6	1.9000	6.1	3.7161	0.2742	7.5	0.2742	14.5
10	1.9741	7.7	1.7988	7.7	3.7729	0.2742	7.5	0.2742	14.5
-10	2.1120	7.8	1.7819	9.5	3.8939	0.2742	7.5	0.2742	14.5
-40	2.3406	8.1	1.7761	13.4	4.1167	0.2742	7.5	0.2742	14.5
-65	2.5409	8.4	1.7754	18.9	4.3163	0.2742	7.5	0.2742	14.5

Table B8 Water Availability Matrix ~ 50% P.H., 50% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LES/HR	MOLE %	H ₂ O IN AIR OUT LES/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LES/HR	MOLE %	H ₂ O IN SAE LES/HR	MOLE %
125	1.6053	12.5	3.9922	9.5	5.5975	0.1920	7.5	0.1920	14.5
100	1.4201	9.6	2.2197	7.2	3.6398	0.1920	7.5	0.1920	14.5
70	1.3663	8.2	1.4895	7.2	2.8558	0.1920	7.5	0.1920	14.5
40	1.4523	7.7	1.2929	10.1	2.7452	0.1920	7.5	0.1920	14.5
10	1.6051	7.8	1.2489	19.0	2.8540	0.1920	7.5	0.1920	14.5
-10	1.7334	8.0	1.2438	34.7	3.1041	0.1920	7.5	0.1920	14.5
-40	1.9444	8.3	1.2429	34.7	3.6239	0.1920	7.5	0.1920	14.5
-65	2.1276	8.5	1.2427	34.7	4.0774	0.1920	7.5	0.1920	14.5

Table B9 Water Availability Matrix - 50% R.H., 25% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	1.0071	12.6	1.7819	10.6	2.7890	0.1051	7.5	0.1051	14.5
100	1.0036	9.4	0.9501	10.9	1.9537	0.1226	7.5	0.1226	12.8
70	1.0072	8.0	0.7008	35.4	1.8044	0.1226	7.5	0.1226	12.8
40	1.1113	7.6	0.6873	34.9	2.1895	0.1226	7.5	0.1226	12.8
10	1.2603	7.7	0.6822	34.8	2.6310	0.1226	7.5	0.1226	12.8
-10	1.3790	7.9	0.6811	34.7	2.9584	0.1226	7.5	0.1226	12.8
-40	1.5711	8.2	0.6806	34.7	3.4813	0.1226	7.5	0.1226	12.8
-65	1.7323	8.5	0.6805	34.7	3.9375	0.1226	7.5	0.1226	12.8

Table B10 Water Availability Matrix - 50% R.H., Hot Idle

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	0.6607	12.9	0.8084	11.6	1.4691	0.0548	7.5	0.0548	14.5
100	0.7527	9.3	0.3833	36.5	1.2590	0.0768	7.5	0.0768	11.5
70	0.7968	8.0	0.3656	35.4	1.5871	0.0768	7.5	0.0768	11.5
40	0.9018	7.6	0.3586	34.9	1.9637	0.0768	7.5	0.0768	11.5
10	1.0443	7.7	0.3559	34.8	2.4007	0.0768	7.5	0.0768	11.5
-10	1.1555	7.9	0.3554	34.7	2.7256	0.0768	7.5	0.0768	11.5
-40	1.3350	8.2	0.3551	34.7	3.2445	0.0768	7.5	0.0768	11.5
-65	1.4914	8.5	0.3551	34.7	3.6970	0.0768	7.5	0.0768	11.5

Table B11 Water Availability Matrix - 100% R.H., 100% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	4.2514	18.5	15.8912	15.5	20.1426	0.3766	7.5	0.3766	14.5
100	3.1591	12.5	7.8438	9.2	11.0029	0.3766	7.5	0.3766	14.5
70	2.5260	9.1	4.0968	6.0	6.6228	0.3766	7.5	0.3766	14.5
40	2.3815	8.0	2.8872	5.2	5.2687	0.3766	7.5	0.3766	14.5
10	2.4638	7.7	2.5304	5.6	4.9942	0.3766	7.5	0.3766	14.5
-10	2.5950	7.8	2.4663	6.3	5.0613	0.3766	7.5	0.3766	14.5
-40	2.8378	8.1	2.4420	7.6	5.2798	0.3766	7.5	0.3766	14.5
-65	3.0574	8.3	2.4386	9.0	5.4960	0.3766	7.5	0.3766	14.5

Table B12 Water Availability Matrix - 100% R.H., 75% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	3.2066	18.5	10.6402	15.8	13.8468	0.2742	7.5	0.2742	14.5
100	2.4328	12.5	5.1986	9.6	7.6314	0.2742	7.5	0.2742	14.5
70	1.9873	9.2	2.7663	6.7	4.7536	0.2742	7.5	0.2742	14.5
40	1.9055	8.0	2.0246	6.5	3.9301	0.2742	7.5	0.2742	14.5
10	1.9987	7.8	1.8223	7.8	3.8210	0.2742	7.5	0.2742	14.5
-10	2.1211	7.9	1.7886	9.5	3.9097	0.2742	7.5	0.2742	14.5
-40	2.3423	8.2	1.7769	13.4	4.1192	0.2742	7.5	0.2742	14.5
-65	2.5412	8.4	1.7754	18.9	4.3166	0.2742	7.5	0.2742	14.5

Table B13 Water Availability Matrix - 100% R.H., 50t Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LEB/HR	MOLE %	H ₂ O IN AIR OUT LEB/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LEB/HR	H ₂ O IN REC LEB/HR	MOLE %	H ₂ O IN SAC LEB/HR	MOLE %
125	2.3669	18.6	6.6841	16.1	9.0510	0.1920	7.5	0.1920	14.5
100	1.8492	12.6	3.1867	10.4	5.0359	0.1920	7.5	0.1920	14.5
70	1.5543	9.3	1.7354	8.4	3.2897	0.1920	7.5	0.1920	14.5
40	1.5230	8.1	1.3430	10.5	2.8660	0.1920	7.5	0.1920	14.5
10	1.6249	7.9	1.2552	19.1	2.8801	0.1920	7.5	0.1920	14.5
-10	1.7412	8.0	1.2449	34.8	3.1132	0.1920	7.5	0.1920	14.5
-40	1.9458	8.3	1.2431	34.7	3.6259	0.1920	7.5	0.1920	14.5
-65	2.1278	8.5	1.2427	34.7	4.0777	0.1920	7.5	0.1920	14.5

Table B14 Water Availability Matrix - 100% R.H., 25% Load

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LEB/HR	MOLE %	H ₂ O IN AIR OUT LEB/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LEB/HR	H ₂ O IN RES LEB/HR	MOLE %	H ₂ O IN SAE LEB/HR	MOLE %
125	1.4806	18.8	2.8603	17.1	4.3409	0.1051	7.5	0.1051	14.5
100	1.3197	12.4	1.2169	14.1	2.5366	0.1226	7.5	0.1226	12.8
70	1.1517	9.1	0.7215	36.0	1.9840	0.1226	7.5	0.1226	12.8
40	1.1671	8.0	0.6940	35.2	2.2721	0.1226	7.5	0.1226	12.8
10	1.2762	7.8	0.6839	34.8	2.6574	0.1226	7.5	0.1226	12.8
-10	1.3850	7.9	0.6817	34.8	2.9689	0.1226	7.5	0.1226	12.8
-40	1.5722	8.2	0.6807	34.7	3.4835	0.1226	7.5	0.1226	12.8
-65	1.7385	8.5	0.6806	34.7	3.9380	0.1226	7.5	0.1226	12.8

Table B15 Water Availability Matrix - 100% R.H., Hot Idle

AMBIENT TEMP, °F	H ₂ O IN FLUE GAS LBS/HR	MOLE %	H ₂ O IN AIR OUT LBS/HR	MOLE %	TOTAL H ₂ O IN EXIT STREAMS LBS/HR	H ₂ O IN RES LBS/HR	MOLE %	H ₂ O IN SAE LBS/HR	MOLE %
125	0.9675	19.0	1.2524	18.1	2.2199	0.0548	7.5	0.0548	14.5
100	0.9933	12.4	0.4134	38.2	1.5708	0.0768	7.5	0.0768	11.5
70	0.9110	9.2	0.3764	36.0	1.7737	0.0768	7.5	0.0768	11.5
40	0.9473	8.0	0.3621	35.2	2.0483	0.0768	7.5	0.0768	11.5
10	1.0575	7.8	0.3568	34.8	2.4276	0.0768	7.5	0.0768	11.5
-10	1.1605	7.9	0.3557	34.8	2.7363	0.0768	7.5	0.0768	11.5
-40	1.3360	8.2	0.3552	34.7	3.2467	0.0768	7.5	0.0768	11.5
-65	1.4915	8.5	0.3551	34.7	3.6974	0.0768	7.5	0.0768	11.5

Appendix: C
Feed Water Requirement

TABLE C1 FEED WATER REQUIREMENT, LBS./HR. - 0% R.H.

AMBIENT TEMP., °F	% LOAD				
	100	75	50	25	HOT IDLE
125	1.5394	1.1375	0.8146	0.4737	0.2763
100	1.6189	1.2081	0.8779	0.5374	0.3729
90	1.6497	1.2357	0.9030	0.5603	0.4315
80	1.6808	1.2636	0.9284	0.5835	0.4912
70	1.7107	1.2908	0.9533	0.6400	0.5515
40	1.8096	1.3793	1.0336	0.8298	0.7400
10	1.9067	1.4672	1.1139	1.0258	0.9349
-10	1.9736	1.5276	1.2190	1.1609	1.0691
-40	2.0764	1.6205	1.4265	1.3701	1.2768
-65	2.1643	1.6999	1.6057	1.5504	1.4556

TABLE C2 FEED WATER REQUIREMENT, LBS./HR. - 50% R.H.

AMBIENT TEMP., °F	% LOAD				
	100	75	50	25	HOT IDLE
125	1.5392	1.1373	0.8145	0.4736	0.2762
100	1.6188	1.2080	0.8779	0.5374	0.3733
70	1.7106	1.2917	0.9533	0.6403	0.5516
40	1.8095	1.3793	1.0336	0.8299	0.7400
10	1.9067	1.4672	1.1139	1.0258	0.9349
-10	1.9736	1.5275	1.2191	1.1609	1.0691
-40	2.0764	1.6205	1.4265	1.3701	1.2768
-65	2.1643	1.6999	1.6057	1.5504	1.4556

TABLE C3 FEED WATER REQUIREMENT, LBS./HR. - 100% R.H.

AMBIENT TEMP., °F	% LOAD				
	100	75	50	25	HOT IDLE
125	1.5389	1.1372	0.8143	0.4735	0.2762
100	1.6186	1.2079	0.8778	0.5373	0.3736
70	1.7106	1.2907	0.9532	0.6407	0.5517
40	1.8095	1.3793	1.0336	0.8300	0.7401
10	1.9067	1.4671	1.1139	1.0258	0.9349
-10	1.9736	1.5275	1.2191	1.1609	1.0691
-40	2.0764	1.6205	1.4265	1.3701	1.2768
-65	2.1643	1.6999	1.6057	1.5504	1.4556

Appendix: D
Percentage Water Recovery Matrix
(100% System Efficiency)

TABLE D1 PERCENTAGE WATER RECOVERY AT 0% R.H. (100% SYSTEM EFFICIENCY)

AMBIENT TEMP., °F	% LOAD				
	100	75	50	25	HOT IDLE
125	0	0	0	0	0
100	1.2	2.1	3.7	23.1	82.6
95	17.5	18.9	21.0	71.8	101.8
90	31.7	33.7	36.5	111.9	122.1
80	55.1	75.6	109.1	168.2	158.2
75	86.3	109.4	137.9	187.9	173.4
70	117.4	136.8	160.6	197.5	185.6
65	143.1	159.3	179.1	205.9	196.3
60	164.3	178.0	194.5	213.1	205.6
55	181.2	192.7	206.3	219.4	213.7
50	195.4	205.1		225.4	220.5
45	207.2	214.9	224.4	230.0	226.2
40	216.3	222.8	229.9	234.1	231.1
10	245.7	247.4	249.3	248.9	248.4
-10	251.1	251.7	252.1	252.1	252.0
-40	253.4	253.6	253.5	253.7	253.7
-65	253.7	253.9	253.9	254.0	254.1

TABLE D2 PERCENTAGE WATER RECOVERY AT 50% R.H. (100% SYSTEM EFFICIENCY)

AMBIENT TEMP., °F	% LOAD				
	100	75	50	25	HOT IDLE
125	0	0	0	0	0
110	29.5	31.1	33.5	67.0	140.8
100	51.1	53.5	84.4	139.6	167.1
90	101.5	120.7	143.4	184.6	189.2
80	152.0	165.7	182.4	211.7	206.6
75	171.1	182.7	196.6	221.5	214.5
70	186.0	195.8	207.9	225.8	220.6
40	235.0	238.6	242.1	244.3	242.8
10	249.7	250.7	251.7	251.6	251.3
-10	252.4	252.8	252.9	252.9	253.0
-40	253.6	253.8	253.6	253.9	253.9
-65	253.8	254.0	253.9	254.0	254.2

TABLE D3 PERCENTAGE WATER RECOVERY AT 100% R.H. (100% SYSTEM EFFICIENCY)

AMBIENT TEMP., °F	% LOAD				
	100	75	50	25	HOT IDLE
125	259.4	259.2	259.2	260.1	261.4
100	256.1	256.3	255.9	256.7	257.0
70	254.6	254.8	254.7	254.8	255.2
40	253.9	254.3	253.7	254.4	254.3
10	253.8	253.9	254.0	254.0	253.9
-10	253.8	253.8	253.7	254.0	254.2
-40	253.9	253.9	253.8	254.0	254.0
-65	253.9	254.0	253.9	254.1	254.2

Appendix: E

Design Calculation for

Air Cooled Exchanger

Required data for hot stream⁽²⁾:

Average temperature = 200°F

Viscosity (μ) = 0.021 cp

Thermal Conductivity (k) = 0.0192 btu/hr ft² (°F/ft)

Heat Load (Q) = 10267 btu/hr

Flow rate (W_t) = 151.7 lbs/hr

Temperature in & out: $T_1 = 307^\circ\text{F}$, $T_2 = 85^\circ\text{F}$

Fouling Factor $r_{dt} = 0.001$

Required data for air:

Ambient temperature (t_1) = 70°F

Basic Assumptions

Type: Forced Draft

Fintube: 1 inch OD with 5/8 inch high fins

Tube pitch: 2 1/4 inch triangular

Trial

Let approximate overall transfer coefficient

U_x be 0.5 btu/hr ft² °F

Approximate Air Temperature Rise

$$\begin{aligned}\Delta t_a &= \frac{(U_x + 1)}{10} \left(\frac{T_1 + T_2}{2} - t_1 \right) \\ &= \frac{0.5 + 1}{10} \left(\frac{307 + 85}{2} - 70 \right) = 19^\circ\text{F}\end{aligned}$$

Corrected Mean Temperature Difference (CMTD):

	°F	°F
Hot Stream	307	85
Air	<u>89</u>	<u>70</u>
	218	15

Log Mean Temperature Difference (LMTD) = 76°F

Assume number of passes (N_p) = 6

∴ correction factor $F = 1$

$$\Delta T_m = \text{LMTD} \times F$$

$$= 76 \times 1 = 76^\circ\text{F}$$

Required Surface:

$$\begin{aligned} A_x &= \frac{Q}{(U_x) (\Delta T_m)} \\ &= \frac{10267}{(0.5) (76)} = 270.2 \text{ ft}^2 \end{aligned}$$

Area per square ft. of bundle face area (APSF) = 178.2

Face Area

$$\begin{aligned} F_a &= \frac{A_x}{\text{APSF}} \\ &= \frac{270.2}{178.2} = 1.516 \text{ ft}^2 \text{ (assume 6 rows)} \end{aligned}$$

Assume length of tube (L) = 2 ft.

$$\begin{aligned} \text{Width} &= \frac{F_a}{L} \\ &= \frac{1.516}{2} = 0.758 \text{ ft} = 9.1 \text{ inches} \end{aligned}$$

Area/ft. of fin tube in square ft. (APF) = 5.58

$$\begin{aligned} \text{No. of tubes } N_t &= \frac{A_x}{(\text{APF}) (L)} \\ &= \frac{270.2}{5.58 (2)} = 25 \end{aligned}$$

Tube inside cross-sectional area (A_t) for 1 inch OD x 16 BWG
tube = 0.5945 square inch

tube side mass velocity

$$G_t = \frac{(144) (W_t) (N_p)}{(3600) (N_t) (A_t)}$$

$$= \frac{144 (151.7) (6)}{(3600) (25) (0.5945)} = 2.449 \text{ lb/sec ft}^2$$

Internal diameter of tube (D_i) = 0.87 inch

Modified Reynolds No.

$$N_R = \frac{(D_i) (G_t)}{\mu}$$

$$= \frac{0.87 \times 2.449}{0.021} = 101.5$$

$$\frac{C_p \mu}{k} = \text{Prandtl No.} = 0.74, J = 660 \text{ (from plot of } J \text{ Vs } N_R)$$

Tube side film coefficient

$$h_t = \frac{J k \left(\frac{C_p \mu}{k} \right)^{1/3} \left(\frac{\mu}{\mu_w} \right)^{0.14}}{D_i}$$

$$= \frac{660 \times 0.0193 (74)^{1/3} \times 1}{0.87} = 13.6 \text{ Btu/hr. ft}^2 \text{ } ^\circ\text{F}$$

Air Flow rate

$$W_a = \frac{Q}{(0.24) (\Delta t_a)} = \frac{10267}{(0.24) (19)} = 2251.5 \text{ lb/hr}$$

Air Face Mass Velocity

$$G_a = \frac{W_a}{F_a}$$

$$= \frac{2251.5}{1.516} = 1485.2 \text{ lb/hr/sq. ft. face area}$$

Air side film coefficient

$$h_a = 6.3 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

Area ratio of fin tube compared to the exterior area of 1 inch

OD bare tube which has 0.262 sq. ft./ft. (AR) = 21.4

$$\frac{A_i}{A_x} = \frac{AR (D_o)}{D_i}$$

A_x is outside extended surface of tube

A_i is inside surface of tube

$$\frac{A_i}{A_x} = \frac{21.4 \times 1.0}{0.87} = 24.6$$

$$\begin{aligned} \frac{1}{U_x} &= \left(\frac{1}{h_t} \right) \left(\frac{A_x}{A_i} \right) + r_{dt} \left(\frac{A_x}{A_i} \right) + r_m + \frac{1}{h_a} \\ &= \frac{1}{13.6} (24.6) + 0.001 (24.6) + \frac{1}{6.3} \end{aligned}$$

$$U_x = 0.502$$

(metal resistance is small compared to other resistances)

Friction factor $f = 0.0032$

Correction factors: $B = 0.0033$, $Y = 3.3$

Tube side pressure drop

$$\begin{aligned} \Delta P_t &= \frac{f Y L N_p}{\phi} + B N_p \\ &= \frac{0.0032 \times 3.3 \times 2 \times 6}{1} + 0.033 \times 6 \\ &= 0.325 \text{ psia} = 9" \text{ H}_2\text{O} \end{aligned}$$

$$\begin{aligned} \text{Minimum fan area/fan (FAPF)} &= \frac{0.4 (F_a)}{(\text{No. fans})} \\ &= \frac{0.4 \times 1.516}{2} = 0.3032 \text{ sq. ft.} \end{aligned}$$

$$\text{Fan Diameter} = \sqrt{\frac{\text{FAPF}}{0.785}} = \sqrt{\frac{0.3032}{0.785}} = 0.621 \text{ ft.}$$

$$\text{Pressure drop factor } F_p = 0.0365$$

$$\text{Density Ratio DR at average air temperature} = 0.98$$

$$\text{Number of rows of tubes (N)} = 6$$

$$\text{Pressure drop factor } F_p = 0.0365$$

Air static pressure drop

$$\begin{aligned} \Delta P_a &= \frac{(F_p)(N)}{(DR)} \\ &= \frac{(0.0365)(6)}{0.98} = 0.223 \text{ inch} \end{aligned}$$

Actual air volume using DR of air at fan

$$\begin{aligned} \text{ACFM} &= \frac{(0.222)(W_a)}{DR} \\ &= \frac{0.222(2251.5)}{1} = 500 \text{ Total} \\ &= 250/\text{fan} \end{aligned}$$

Approximate fan total pressure using DR of air at fan

$$\begin{aligned} \text{PF} &= p_a + \left[\frac{\text{ACFM}}{4000 \left(\frac{3.14 D^2}{4} \right)} \right]^2 (DR) \\ &= 0.223 + \left(\frac{250}{4000 \left(\frac{3.14 \times 8^2}{4 \times 12} \right)} \right)^2 (1.0) \\ &= 0.275 \end{aligned}$$

Approximate horse power per fan

$$\begin{aligned} H_p &= \frac{(\text{ACFM}/\text{fan})(\text{PF})}{(6370)(0.70)} \\ &= \frac{250 \times 0.275}{6370 \times 0.7} = 0.0154 \text{ H.P.} \\ &= 11.5 \text{ watts} \end{aligned}$$

Tube side power requirement:

Volumetric flow rate $V = 2917.3 \text{ ft}^3/\text{hr}$

$\Delta P_t = 0.325 \text{ psi}$

Work = $V \Delta P_t = 2917.3 \times 0.325 \times (144/3600) \times 1.356$
= 51 watts

Total Parasitic Power = $23 + 51 = 74 \text{ watts}$

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